Les Cahiers du GERAD ISSN: 0711–2440

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G–2017–45

June 2017

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The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

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Vehicle routing and location-routing with intermediate stops: A review

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June 2017

Les Cahiers du GERAD
G–2017–45

Abstract: This paper reviews the literature on vehicle routing problems and location-routing problems with intermediate stops. Besides providing concise paper excerpts that convey the central ideas of each source, we classify publications into different categories from both an application-based perspective and a methodological perspective. In addition, we analyze the papers with respect to the algorithms and benchmark instances they present. Furthermore, we provide an overview of trends in literature and identify promising areas for further research.

Keywords: Intermediate stops, intra-route facilities, vehicle routing, location-routing, survey

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Acknowledgments: Gilbert Laporte was partially funded by the Canadian Natural Sciences and Engineering Research Council under grant 2015-06189. This support is gratefully acknowledged.

1 Introduction

Routing problems with intermediate stops (RPIS) are highly relevant in logistics, arising e.g., in freight transportation and municipal waste collection. However, research interests on these problems have for a long time mainly been limited to single application cases. In recent years, researchers have paid increasing attention to routing problems with intermediate stops, especially regarding applications in city logistics and logistics fleets with alternative fuel vehicles (AFVs). The purpose of this review is to guide the reader through the literature on routing problems with intermediate stops by providing a discussion on research fields, application cases and methodological classifications. Our discussion assumes that the reader has a basic knowledge of vehicle routing (cf. Golden et al., 2008; Toth and Vigo, 2014), location theory (cf. Daskin, 1995; Laporte et al., 2015), and exact and heuristic solution methods for combinatorial optimization problems in general (cf. Wolsey, 1998; Desaulniers et al., 2005; Funke et al., 2005; Gendreau and Potvin, 2010).

We start the discussion with a precise definition of the terms *intermediate stop* and *intra-route facility.* These terms are necessary to characterize our problem class, but are ambiguously used in literature and in different research streams. In this work, an intermediate stop is an optional stop en route in order to keep a vehicle operational while fulfilling its main service task. Thus, an intermediate stop differs from a regular stop (e.g., providing service at a customer) and must also not be confounded with an optional customer stop that arises e.g., in vehicle routing problems (VRPs) with profits (cf. Archetti et al., 2014). Although intermediate stops are optional, they may prove unavoidable to keep vehicles operational. Intermediate stops take place at so-called intra-route facilities, which enable vehicles to replenish a certain resource. An intra-route facility is planned at the same echelon as the customers. It is visited en route and thus differs from an intermediate facility, which is often used as a synonym for a depot or a hub in multi-echelon and cross-docking operations. Therefore, we exclude work on multi-echelon routing problems from this survey and refer to Guastaroba et al. (2016) for a deep overview of this topic.

Before detailing the aim and organization of this survey, we first outline application areas in which routing problems with intermediate stops arise. Next, we show how these problems can be categorized from a methodological point of view cutting across these application areas. Both, the application-based and the methodological classification are then used to organize this survey in a concise fashion.

Application areas

Since the early 1970s, researchers studied RPIS. While this research was very sparse until the year 2000, it increased significantly from then on due to new challenges arising in city logistics and AFV fleets. More precisely, RPIS arise in three main application areas:

i) *Replenishment and disposal of goods or waste:* In certain distribution networks, satellite facilities are used to avoid deadheads that arise out of back-trips to the depot to replenish freight (cf. Angelelli and Speranza, 2002b; Crevier et al., 2007; Tarantilis et al., 2008). Real-world examples for such a distribution structure can be found in heating oil distribution (Prescott-Gagnon et al., 2014), road maintenance (Amaya et al., 2007), and city logistics (Crainic et al., 2009). Analogous concepts can be used to dispose freight in collecting problems. Two main application areas arise in this context, namely waste collection (cf. Kim et al., 2006; Benjamin and Beasley, 2010) and snow plowing (cf. Perrier et al., 2006a; Salazar-Aguilar et al., 2012).

ii) *Refueling:* Routing problems with refueling stops are encountered in dense or in sparse refueling network structures. In dense network structures, problems arise for economic reasons (e.g., company contracts with lower prices or large price differences between stations in a close vicinity). If AFVs are used as sustainable means of transportation, the necessary refueling infrastructure for new technologies is still sparse. Additionally, the driving range may be limited, e.g., for electric commercial vehicles (ECVs). Thus, refueling stops have to be considered explicitly in the respective routing problems.

iii) *Idling for rest periods and breaks:* Focusing on long-haul distribution or multi-day trips, intermediate stops for idling times arise because of hours of service (HOS) regulations in freight transportation (Goel, 2009) or due to hotel selection (Vansteenwegen et al., 2012) to prevent drivers' fatigue.

The research interest in these three application areas evolved differently in the last years. Figure 1 shows this development by illustrating the total number of publications over time. Intermediate stops for replenishing

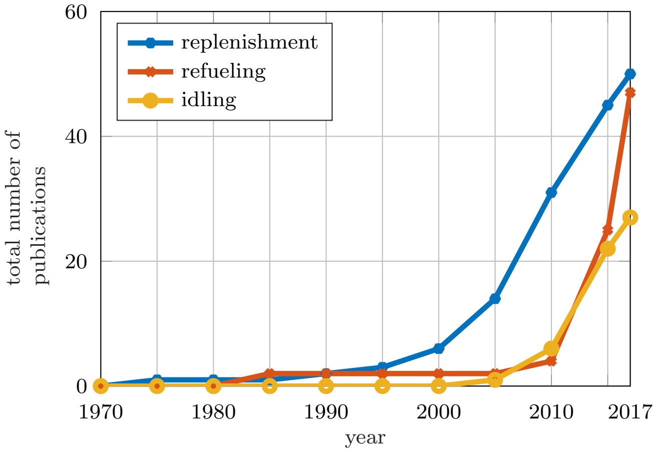

Figure 1: Total number of publications over time for the three application areas.

or unloading were studied first, and the number of papers on this topic is constantly rising. Herein, papers mainly focus on conventional applications in municipal services (e.g., waste collection) and logistics systems (e.g., freight replenishment), which have been and still are relevant for practitioners. Up to 2010, papers on refueling issues were mainly limited to routing of internal combustion engine vehicles (ICEVs) in a dense infrastructure. Due to a significant interest of researchers and practitioners in routing problems with AFVs, especially ECVs, one can recognize a huge increase in the number of papers from then on. Publications on intermediate stops for idling for HOS regulations and hotel selection in routing problems increased mainly between the year 2000 and 2015.

Methodological categorization

Routing problems on intermediate stops can also be classified with regard to a methodological nomenclature. This nomenclature highlights the characteristics of different problem variants with respect to modeling constraints (cf. Schiffer et al., 2017b). Common characteristics are time constraints, i.e., problem variants with a maximum route duration and problem variants restricted to (multiple) time windows at customers. Routing problems for intermediate stops can be further differentiated with respect to the characteristics of the replenishment process, which is closely linked to overall time constraints if replenishment is time-consuming. In addition, the replenished resource (from here on referred to as the operational resource) can differ with respect to its consumption. Detailing the characteristics listed above, the following nomenclature to characterize routing problems with intermediate stops can be derived:

i) *Time constraints* can be given either by time windows (TW) or by a maximum route duration (MRD) or can be neglected (none).
ii) *Replenishment time* can either be dependent (D) or independent (I) of the quantity of the operational resource that has to be replenished.
iii) *Replenishment processes* can either be constrained as full replenishment (F) or as partial replenishment (P).
iv) *Operational resources* can be characterized due to the consumption of the operational resource, which can either be node-based (N) (e.g., freight) or arc-based (A) (e.g., fuel).

The resulting nomenclature is shown in Table 1. As can be seen, problems are basically separated into node-based and arc-based problems in the first dimension. Further, problems can be characterized by the type of time restrictions. The second dimension divides these problems further into quantity-dependent and quantity-independent replenishment processes. Quantity-dependent processes can be further separated into full and partial replenishment processes. Partial replenishment is not considered for time-independent models because the time savings it yields are irrelevant.

Aim and organization

This survey makes a twofold contribution. First, the past, current, and future application areas for routing

Table 1: Nomenclature of VRP with intermediate stops (VRPIS) variants.

		Dependent replenishment		Independent replenishment
Consumption	Time restriction	Full replenishment	Partial replenishment	Full replenishment
node based	none	NDF	NDP	NIF
	route duration	NDFMRD	NDPMRD	NIFMRD
	time windows	NDFTW	NDPTW	NIFTW
arc based	none	ADF	ADP	AIF
	route duration	ADFMRD	ADPMRD	AIFMRD
	time windows	ADFTW	ADPTW	AIFTW

In analogy to Schiffer et al. (2017b).

problems with intermediate stops are highlighted to provide researchers a knowledge of the development of this research field over time. Second, methodological enhancements and problem specific details are discussed. This survey contains a dedicated section for each application area. Within these sections, the application areas are further separated into sections on specific research streams and one analysis section for each application area that summarizes its main findings. The nomenclature presented in Table 1 is used in the analysis section to highlight the methodological contributions and the focus of each application area and research stream. We pay special attention to the discussion of the following aspects: *i*) We analyze the scope of each publication, mainly dividing between case studies and algorithmic contributions. In this context, we count a publication only as a case study paper if it is based on a real-world dataset and problem, and is of interest for practitioners. Thus, papers that derive only instance sets from real-world data without any context or discussion are regarded as methodological papers. Furthermore, we subdivide publications into arc routing and node routing problems and we discuss the type of data with respect to deterministic and uncertain information. *ii*) We analyze the various objectives used within the application field and discuss their relevance. *iii*) To show which algorithms are most suitable and popular for the specific application area, we discuss the different solution methods that have been developed. This discussion is split into a part on exact algorithms and a part on metaheuristics. *iv*) We provide information on the available benchmarks for each research steam. Finally, we summarize the main findings for each application area and discuss future research questions.

The remainder of this paper is structured as follows. Section 2 reviews literature on intermediate stops for replenishment and unloading. Section 3 focuses on intermediate stops for refueling. Section 4 analyzes literature on intermediate stops for idling due to breaks or rests. Section 5 concludes this survey by summarizing its main findings. In the Appendix, we provide a glossary of the abbreviations used in this paper.

2 Intermediate stops for replenishment or disposal of goods

In this section, we focus on publications that address intermediate stops for the replenishment or the disposal of goods. Classical application cases often arise in retail and distribution logistics and municipal services. Besides these classical problems, selected VRPs with synchronization constraints (especially transshipment problems) represent RPIS according to our definition in Section 1. Accordingly, Section 2.1 focuses on intermediate stops for replenishment, while Section 2.2 focuses on intermediate stops for unloading. Transshipment and synchronization problems are discussed in Section 2.3. In Section 2.4, we conduct an analysis of problem characteristics and solution methods.

2.1 Intermediate stops for goods replenishment

Intermediate stops for goods replenishment often arise in distribution networks for raw materials or in a package shipping context.

The first publication that introduced intermediate stops in this context focused on propane gas distribution. Bard et al. (1998) addressed the VRP with satellite facilities and developed a branch-and-cut (BC) algorithm for this problem. The objective is to minimize the overall distance under a maximum tour duration constraint. Another application in raw material distribution was discussed by Prescott-Gagnon et al. (2014) who proposed a VRP arising in heating oil distribution, considering intra-route replenishments, heterogeneous vehicles, optional customer visits and time windows. The authors designed a tabu search (TS) heuristic, a large neighborhood search (LNS) heuristic with a TS component and a column generation (CG) metaheuristic to analyze a real-world instance.

Focusing on replenishment for parcel logistics, several publications focused on arc routing as well as node routing problems. Focusing on arc routing problems, Ghiani and co-authors investigated the capacitated arc routing problem (CARP) with intermediate facilities (CARPIF) in several publications. Ghiani et al. (2001) introduced the CARPIF as an extension of the pure CARP, accounting for intermediate stops for replenishment or unloading. The authors presented a lower bound based on the rural postman problem and a linear integer program. Ghiani et al. (2004) extended the CARPIF for capacity and length restrictions and developed three heuristics, namely a construction algorithm and two TS algorithms. Ghiani et al. (2010) provided an ant colony algorithm for the CARPIF that outperformed existing algorithms. Polacek et al. (2008) presented a variable neighborhood search (VNS) for the CARP with refill points (CARPRP) that was capable of finding the best known solution (BKS) for all 120 instances of four different benchmark sets for the CARP and the CARPRP, and improved 71 BKSs.

Focusing on node routing problems, Angelelli and Speranza (2002b) extended the periodic VRP (PVRP) to intermediate facilities. Minimizing the overall traveled distance, they proposed a TS heuristic for this problem and presented results on instances with 50–288 customers. Crevier et al. (2007) introduced the multi-depot VRP with inter-depot routes (MDVRPI), which considers intermediate depots where vehicles can be replenished during the course of a route. Tarantilis et al. (2008) renamed this problem to the VRP with intermediate replenishment facilities (VRPIRF) and proposed a hybrid guided local search (LS) heuristic. Kek et al. (2008) studied a capacitated VRP (CVRP) with flexible start and end depots, allowing for intermediate replenishment visits to any depot. The authors presented a mixed integer program to minimize travel and vehicle costs, and found that cost savings of 49% can be reached for a specific case study in Singapore. Muter et al. (2014) developed a branch-and-price algorithm for the MDVRPI. The authors discussed the benefit of two different pricing subproblems and managed to solve problem instances up to 50 customers to optimality.

Recent publications focused on generic algorithmic frameworks for RPIS. Schneider et al. (2015) introduced the VRPIS and provided results on different problems. Schiffer et al. (2017b) focused on the VRPIS by analyzing different types of resources and replenishment options, and presented an algorithmic framework that yields new BKSs for most existing problem types. Both publications also investigated the MDVRPI benchmarks of Crevier et al. (2007) and Tarantilis et al. (2008).

2.2 Intermediate stops for unloading of goods

Intermediate stops for unloading of goods arise in municipal service applications, especially in waste collection problems. For an in-depth overview on waste collection problems that does not only cover problems related to intermediate stops, we refer to Beliën et al. (2014).

The first publication on intermediate stops for unloading was by Beltrami and Bodin (1974) focusing on routing of waste collection vehicles with disposal facilities for a real-world problem arising in New York and Washington. Mouro and Almeida (2000) investigated a CARP with intermediate stops for a household refuse problem in Lisbon. A lower bound as well as a route-first cluster-second heuristic were presented, and the algorithm was tested on a benchmark set based on the real-world case. Mouro and Amado (2005) presented another heuristic for this problem based on a multi-graph representation, which improved their previous results and performed well on large-sized instances with up to 400 nodes and 1215 arcs. Angelelli and Speranza (2002a) applied the periodic VRP with intermediate facilities (PVRP) originally presented in Angelelli and Speranza (2002b) to case studies arising in waste collection. The authors presented a TS heuristic to solve large instances. De Rosa et al. (2002) introduced the arc routing and scheduling problem with transshipment as a variant of the CARPRP. The problem arises in urban waste collection, where a fleet of vehicles recollects garbage, which is delivered to transfer stations and processed into compact units, and then transported to its final destination by trucks. Ghiani et al. (2005) applied the CARPIF to a waste collection problem in southern Italy, presenting a cluster-first route-second heuristic. Del Pia and Filippi (2006) studied a real-world case on waste collection in northern Italy using a CARP with intermediate stops. The authors implemented a VNS algorithm and found that a significant reduction in overall time (approx. 30%) can be achieved compared to the current real-world solution. Another real-world case of a waste management company was studied by Kim et al. (2006), who extended Solomon's insertion algorithm for this problem. Besides the case study, an instance set for the VRP with time windows (VRPTW) was considered. Santos et al. (2008) investigated a CARP with intermediate stops at drop-off points for a waste collection problem in Portugal. The authors implemented a decision support system based on a path-scanning algorithm. Benjamin and Beasley (2010) focused on the waste collection VRP with multiple disposal facilities and considered time windows and driver rest periods as well. Coene et al. (2010) discussed a PVRP in the context of waste collection, and presented a route-first cluster-second algorithm. Buhrkal et al. (2012) focused on a waste collection VRP in a city logistics context, considering time windows and minimizing the overall costs. In addition to numerical studies on existing benchmarks, the authors provided a case study of a Danish garbage company and proved that their algorithm is capable of improving the real-world results. Hemmelmayr et al. (2013a) and Hemmelmayr et al. (2013b) also studied the PVRP in the context of waste collection. The authors introduced a hybrid solution approach consisting of a VNS with a dynamic programming (DP) component. This solution procedure outperformed the approaches of Crevier et al. (2007) and Tarantilis et al. (2008) on the MDVRPI instances. Markov et al. (2016) studied the waste collection VRP with intermediate facilities and investigated the impact of a heterogeneous fleet and flexible destination depots. A case study based on data of a waste company in Switzerland was presented, and the developed VNS obtains a mean improvement of 14.46% on the real-world solution. Willemse and Joubert (2016) investigated four different construction heuristics for the mixed CARPRP under time restrictions, aiming to identify a suitable heuristic for real-time support in real-world application cases.

Single publications on intermediate stops for unloading focused on other topics than waste collection. Jordan (1987) investigated a VRP with additional backhauls that can be stored at intermediate facilities instead of the home-depot. The authors presented a matching problem and a greedy heuristic to solve this problem. An extensive survey on snow clearance was given in Perrier et al. (2006a,b, 2007a,b). In this context, Perrier et al. (2007b) discussed VRPs with intermediate stops for unloading operations in snow plowing as well.

2.3 Intermediate stops for transshipment and synchronization

Routing problems with synchronization constraints cover a wide range of application fields (cf. Drexl, 2012). However, not all of these problems represent intermediate stops, according to our definition in Section 1. Therefore, we limit the following discussion to synchronization problems that include an intermediate stop, and we refer to Drexl (2011, 2012) for an extensive overview on synchronization problems in general.

The publications discussed in the following can be separated into truck and trailer routing problems (TTRPs) and other routing problems with synchronization constraints. TTRPs are routing problems in which some customers can be served by trucks carrying a trailer, and other customers can only be served by a truck without a trailer. Thus, trailers can be parked and later be picked up by trucks if needed and allowed. In this way, freight can be transferred between trucks by picking up or dropping trailers. In TTRPs, the parking space for trailers can be seen as an intra-route facility. In other synchronization problems, the interchange of freight is conducted between two vehicles directly. In this case, designated support vehicles can be seen as mobile intra-route facilities.

We limit our discussion to synchronization problems in which the synchronization or the transshipment is limited to locations at a single echelon and occurs en route. Thus, multi-echelon synchronization problems (e.g., Contardo et al., 2012) are not considered. According to our definition in Section 1, intermediate stops that are directly related to providing service are not considered. This means that we also exclude dial-a-ride problems (e.g., Gørtz et al., 2009) and school bus routing (e.g., Russell and Morrel, 1986; Fügenschuh, 2009) from our analysis. Furthermore, we exclude publications on staff and driver scheduling (e.g., Lim et al., 2004;

Li et al., 2005; Zäpfel and Bögl, 2008; Dohn et al., 2009) because here intermediate stops are neither linked to an intermediate facility nor to a support vehicle.

An overview on TTRPs can be found in Drexl (2013) and Cuda et al. (2015). The first publication focusing on trailers in a VRP is due to Semet and Taillard (1993). The authors analyzed a real-world application on a grocery store distribution network and presented a TS heuristic. Gerdessen (1996) discussed the VRP with trailers allowing trucks to leave the trailer at a parking space and developed construction heuristics as well as a LS to solve the problem. Chao (2002) presented a TS heuristic for the TTRP. The algorithm was evaluated on instances with up to 150 customers. Scheuerer (2006) presented two construction heuristics and a TS heuristic for the TTRP. The algorithm outperformed the results of Chao (2002) on all instances. Tan et al. (2006) focused on the TTRP, investigating a multi-objective function, minimizing the distance and the number of trucks using an evolutionary algorithm. Villegas et al. (2010) presented a greedy randomized adaptive search procedure (GRASP), and a VNS with evolutionary LS for the single TTRP with time windows. Caramia and Guerriero (2010) presented a matheuristic for the TTRP based on a mixed integer program (MIP) and a LS procedure. Villegas et al. (2011) provided a combination of GRASP, VNS, and path relinking for the TTRP, which outperformed all previous algorithms. Derigs et al. (2013) focused on the TTRP and discussed the impact of time windows and load transfers between trucks and trailers. Villegas et al. (2013) presented a matheuristic for the TTRP, consisting of a GRASP with iterated LS (ILS) and a set partitioning formulation. Drexl (2014) presented five different BC algorithms for the TTRP with transshipments and evaluated them on a large set of benchmark instances derived from real-world problems. Belenguer et al. (2016) discussed the single TTRP and included satellite facilities at which the trailer must be parked. The authors presented a BC algorithm capable of solving instances with up to 100 customers and 20 satellite facilities. Rothenbächer et al. (2016) developed a branch-and-price-and-cut (BPC) algorithm for the TTRP with time windows, considering quantity-dependent transfer time. It outperformed existing approaches on known benchmark instances and was also applied to two real-world problems. Parragh and Cordeau (2017) focused on the TTRP with time windows in the context of infrastructure service providers that operate in urban areas. The authors developed a branch-and-price (BP) algorithm and an adaptive LNS (ALNS) to create initial columns and manage to solve instances up to 100 customers to optimality.

Other routing problems with synchronization constraints arise in municipal as well as logistics services. Amaya et al. (2007) introduced the CARPRP in the context of road painting. Here, a vehicle that provides service on arcs is refilled at certain service points (in this case road junctions) by a second vehicle. In Amaya et al. (2010), the authors presented a route-first cluster-second heuristic and a cutting-plane algorithm for the CARPRP and extended it to multiple loads. Using this heuristic, they solved a real-world case arising for road painting in Quebec. Salazar-Aguilar et al. (2012) studied an arc routing problem with synchronization constraints for snow plowing vehicles and presented an ALNS to study real-world large-sized instances. Salazar-Aguilar et al. (2013) focused on node and arc routing in the context of road painting and minimize the makespan. The authors developed an ALNS that provided good results on a large set of artificial instances.

Lin (2008) focused on a pickup and delivery VRP in which transfers between vehicles are allowed. Qu and Bard (2012) investigated a pickup and delivery problem with transshipment. The authors developed a GRASP heuristic that proved competitiveness with existing methods on pickup and delivery benchmarks and introduced a new benchmark set. Rais et al. (2014) proposed mixed integer programs for the VRP with pickup and delivery and transshipment with time windows.

2.4 Analysis of intermediate stops for replenishment and unloading

We now outline the characteristics of the publications discussed in Sections 1–3 with respect to their overall scope, objectives, and algorithmic contributions. Table 2 shows the scope of these papers, differentiating them for *i*) the type of contribution (case study vs. methodological), *ii*) the type of the routing problem (node routing vs. arc routing), *iii*) the type of replenishment (unloading vs. replenishment vs. transshipment), and *iv*) the type of data (deterministic vs. uncertain).

As can be seen from Figure 2, a large majority of the publications focus on a methodological contribution (63%), while only 37% focus on application cases. Detailing this ratio in Table 2, it can be seen that

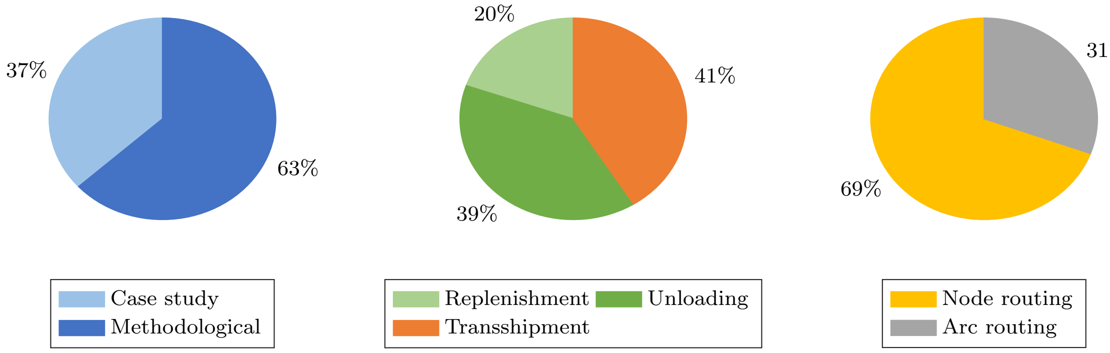

Figure 2: Characteristics of publications on intermediate stops for replenishment and unloading.

Table 2: Scope of publications on intermediate stops for replenishment and unloading of goods.

Case Study	Beltrami and Bodin (1974); Semet and Taillard (1993); Mouro and Almeida (2000); Angelelli and Speranza (2002a); Ghiani et al. (2005); Mouro and Amado (2005); Del Pia and Filippi (2006); Kim et al. (2006); Kek et al. (2008); Santos et al. (2008); Amaya et al. (2010); Coene et al. (2010); Buhrkal et al. (2012); Salazar-Aguilar et al. (2012); Hemmelmayr et al. (2013b); Prescott-Gagnon et al. (2014); Markov et al. (2016); Willemse and Joubert (2016)
Methodological	Jordan (1987); Gerdessen (1996); Bard et al. (1998); Ghiani et al. (2001); Angelelli and Speranza (2002b); Chao (2002); De Rosa et al. (2002); Ghiani et al. (2004); Scheuerer (2006); Tan et al. (2006); Amaya et al. (2007); Crevier et al. (2007); Lin (2008); Polacek et al. (2008); Tarantilis et al. (2008); Benjamin and Beasley (2010); Ghiani et al. (2010); Villegas et al. (2010, 2011); Qu and Bard (2012); Derigs et al. (2013); Hemmelmayr et al. (2013a); Salazar-Aguilar et al. (2013); Drexl (2014); Muter et al. (2014); Rais et al. (2014); Schneider et al. (2015); Belenguer et al. (2016); Rothenbächer et al. (2016); Willemse and Joubert (2016); Parragh and Cordeau (2017)
Node routing	Beltrami and Bodin (1974); Jordan (1987); Semet and Taillard (1993); Gerdessen (1996); Bard et al. (1998); Angelelli and Speranza (2002b,a); Chao (2002); Kim et al. (2006); Scheuerer (2006); Tan et al. (2006); Crevier et al. (2007); Kek et al. (2008); Lin (2008); Tarantilis et al. (2008); Benjamin and Beasley (2010); Coene et al. (2010); Villegas et al. (2010, 2011); Buhrkal et al. (2012); Qu and Bard (2012); Derigs et al. (2013); Hemmelmayr et al. (2013a,b); Salazar-Aguilar et al. (2013); Drexl (2014); Muter et al. (2014); Prescott-Gagnon et al. (2014); Rais et al. (2014); Schneider et al. (2015); Belenguer et al. (2016); Markov et al. (2016); Rothenbächer et al. (2016); Parragh and Cordeau (2017)
Arc routing	Mouro and Almeida (2000); Ghiani et al. (2001); De Rosa et al. (2002); Ghiani et al. (2004, 2005); Mouro and Amado (2005); Del Pia and Filippi (2006); Amaya et al. (2007); Polacek et al. (2008); Santos et al. (2008); Amaya et al. (2010); Ghiani et al. (2010); Salazar-Aguilar et al. (2012, 2013); Willemse and Joubert (2016)
Replenishment	Bard et al. (1998); Ghiani et al. (2001, 2004); Tan et al. (2006); Crevier et al. (2007); Kek et al. (2008); Tarantilis et al. (2008); Ghiani et al. (2010); Muter et al. (2014); Prescott-Gagnon et al. (2014); Schneider et al. (2015)
Unloading	Beltrami and Bodin (1974); Jordan (1987); Mouro and Almeida (2000); Ghiani et al. (2001); Angelelli and Speranza (2002b,a); De Rosa et al. (2002); Ghiani et al. (2004, 2005); Mouro and Amado (2005); Del Pia and Filippi (2006); Kim et al. (2006); Polacek et al. (2008); Santos et al. (2008); Benjamin and Beasley (2010); Coene et al. (2010); Ghiani et al. (2010); Buhrkal et al. (2012); Hemmelmayr et al. (2013b,a); Markov et al. (2016); Willemse and Joubert (2016)
Transshipment	Semet and Taillard (1993); Gerdessen (1996); Chao (2002); Scheuerer (2006); Amaya et al. (2007); Lin (2008); Amaya et al. (2010); Caramia and Guerriero (2010); Villegas et al. (2010); Drexl et al. (2013); Villegas et al. (2011); Drexl (2012); Qu and Bard (2012); Salazar-Aguilar et al. (2012); Derigs et al. (2013); Drexl (2013); Salazar-Aguilar et al. (2013); Villegas et al. (2013); Drexl (2014); Rais et al. (2014); Belenguer et al. (2016); Rothenbächer et al. (2016); Parragh and Cordeau (2017)
Deterministic	Beltrami and Bodin (1974); Jordan (1987); Semet and Taillard (1993); Gerdessen (1996); Bard et al. (1998); Mouro and Almeida (2000); Ghiani et al. (2001); Angelelli and Speranza (2002b,a); Chao (2002); De Rosa et al. (2002); Ghiani et al. (2004, 2005); Mouro and Amado (2005); Del Pia and Filippi (2006); Kim et al. (2006); Scheuerer (2006); Tan et al. (2006); Amaya et al. (2007); Crevier et al. (2007); Kek et al. (2008); Lin (2008); Polacek et al. (2008); Santos et al. (2008); Tarantilis et al. (2008); Amaya et al. (2010); Benjamin and Beasley (2010); Coene et al. (2010); Ghiani et al. (2010); Villegas et al. (2010, 2011); Buhrkal et al. (2012); Qu and Bard (2012); Salazar-Aguilar et al. (2012); Derigs et al. (2013); Hemmelmayr et al. (2013a,b); Salazar-Aguilar et al. (2013); Drexl (2014); Muter et al. (2014); Prescott-Gagnon et al. (2014); Rais et al. (2014); Schneider et al. (2015); Belenguer et al. (2016); Markov et al. (2016); Rothenbächer et al. (2016); Willemse and Joubert (2016); Parragh and Cordeau (2017)
Stochastic	None

most case studies are presented in the context of municipal services (e.g., waste collection, snow plowing), while publications addressing goods replenishment for classical logistics services often focus on algorithmic enhancements. The ratio between node routing (69%) and arc routing (31%) also indicates the share of different application cases in the analyzed publications. Arc routing problems are mainly discussed for municipal operations, and thus are related to road services or maintenance, e.g., snow plowing (Perrier et al., 2007a), waste collection (Del Pia and Filippi, 2006), and road painting (Amaya et al., 2007). Node routing problems are mainly discussed for classical logistics applications in which the service operation is related to single customer locations. Most publications focus on unloading (39%) or transshipment and synchronization (41%), while only 20% focus on replenishment operations (cf. Figure 2). However, some of the synchronization problems arise in replenishment operations, e.g., (Amaya et al., 2007, 2010). While a large majority of the publications focusing on unloading is related to waste collection, additional application cases for unloading problems arise in pickup problems in logistics networks, e.g., in milk collection (cf. Rothenbächer et al., 2016). Focusing on the type of data, none of the publications addresses uncertain data.

To describe the characteristics of the proposed problems with respect to time and replenishment or unloading restrictions, Figure 3 and Table 3 categorize the problem variants as outlined in Section 1. Most problems have a maximum route duration, while only 30% are constrained by time windows. The reason can be seen in the underlying application cases: waste collection, other municipal services, and most of the addressed logistics services (e.g., heating oil distribution) are only limited to a daily planning horizon. Therefore, time windows only arise in specific application cases or in pure methodological contributions to challenge the algorithms.

Table 4 and Figure 4 provide a summary of the objectives. As can be seen, most publications focus on cost or distance minimization. Furthermore, the minimization of the overall route duration or of the number of vehicles is typically considered. Only a few publications minimize the makespan of the longest tour in order to obtain tours of similar durations (cf. Salazar-Aguilar et al., 2012, 2013).

Table 5 details the solution approaches that have been used to solve routing problems with intermediate stops for replenishment or unloading. To keep the table concise, we limited the solution methods listed in the heuristic section to algorithms that are used in more than one paper, and merge certain algorithms in their respective class (e.g., two-phase algorithms contain route-first cluster-second algorithms). The majority

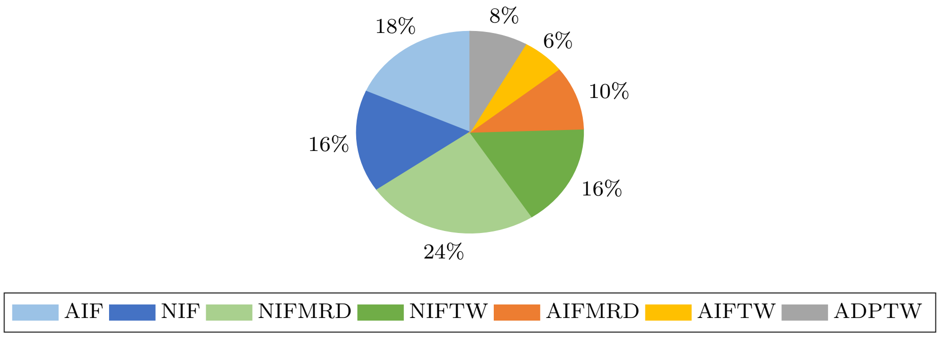

Figure 3: Types of problem variants for intermediate stops for replenishment and unloading.

Table 3: Types of problem variants for intermediate stops for replenishment and unloading.

AIF	Mouro and Almeida (2000); Ghiani et al. (2001); Mouro and Amado (2005); Del Pia and Filippi (2006); Amaya et al. (2007); Santos et al. (2008); Amaya et al. (2010); Salazar-Aguilar et al. (2012, 2013); Belenguer et al. (2016)
NIF	Beltrami and Bodin (1974); Jordan (1987); Gerdessen (1996); Angelelli and Speranza (2002b); Chao (2002); Scheuerer (2006); Lin (2008); Villegas et al. (2011)
NIFMRD	Bard et al. (1998); Crevier et al. (2007); Kek et al. (2008); Tarantilis et al. (2008); Benjamin and Beasley (2010); Coene et al. (2010); Buhrkal et al. (2012); Hemmelmayr et al. (2013a,b); Muter et al. (2014); Schneider et al. (2015); Willemse and Joubert (2016)
NIFTW	Kim et al. (2006); Benjamin and Beasley (2010); Villegas et al. (2010); Buhrkal et al. (2012); Qu and Bard (2012); Drexl (2014); Prescott-Gagnon et al. (2014); Rais et al. (2014); Markov et al. (2016)
AIFMRD	De Rosa et al. (2002); Ghiani et al. (2004); Tan et al. (2006); Polacek et al. (2008); Ghiani et al. (2010)
AIFTW	Semet and Taillard (1993); Kim et al. (2006); Derigs et al. (2013); Parragh and Cordeau (2017)
ADPTW	Rothenbächer et al. (2016)

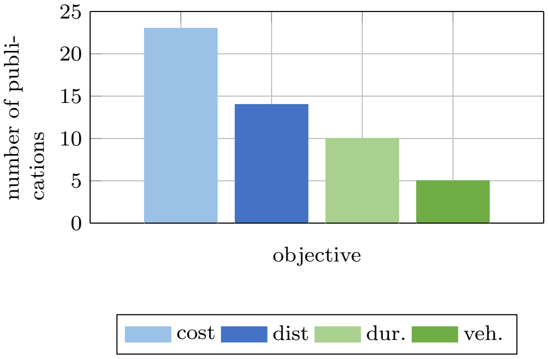

Figure 4: Objectives for intermediate stops for replenishing and unloading.

Table 4: Objectives for intermediate stops for replenishing and unloading.

Objective	References
min. costs	Mouro and Almeida (2000); Ghiani et al. (2001); De Rosa et al. (2002); Ghiani et al. (2004, 2005); Mouro and Amado (2005); Amaya et al. (2007); Crevier et al. (2007); Kek et al. (2008); Lin (2008); Polacek et al. (2008); Amaya et al. (2010); Ghiani et al. (2010); Buhrkal et al. (2012); Hemmelmayr et al. (2013a,b); Drexl (2014); Schneider et al. (2015); Belenguer et al. (2016); Markov et al. (2016); Rothenbächer et al. (2016); Willemse and Joubert (2016); Parragh and Cordeau (2017)
min. distance	Jordan (1987); Semet and Taillard (1993); Bard et al. (1998); Angelelli and Speranza (2002b,a); Chao (2002); Scheuerer (2006); Tan et al. (2006); Benjamin and Beasley (2010); Villegas et al. (2010, 2011); Derigs et al. (2013); Prescott-Gagnon et al. (2014); Rais et al. (2014)
min. duration	Beltrami and Bodin (1974); Gerdessen (1996); Del Pia and Filippi (2006); Kim et al. (2006); Santos et al. (2008); Tarantilis et al. (2008); Coene et al. (2010); Salazar-Aguilar et al. (2012, 2013); Muter et al. (2014)
min. vehicles	Beltrami and Bodin (1974); Kim et al. (2006); Tan et al. (2006); Qu and Bard (2012); Willemse and Joubert (2016)

Table 5: Solution methods for routing problems on intermediate stops for replenishment and unloading.

	Exact
(M)I(L)P	Jordan (1987); Bard et al. (1998); Mouro and Almeida (2000); Ghiani et al. (2001); Chao (2002); Amaya et al. (2007); Crevier et al. (2007); Kek et al. (2008); Lin (2008); Amaya et al. (2010); Coene et al. (2010); Buhrkal et al. (2012); Hemmelmayr et al. (2013a,b); Drexl (2014); Rais et al. (2014); Schneider et al. (2015); Belenguer et al. (2016); Markov et al. (2016)
BC	Bard et al. (1998); Amaya et al. (2010); Drexl (2014); Belenguer et al. (2016)
DP component	Hemmelmayr et al. (2013a); Schiffer et al. (2017b)
BP, CG	Muter et al. (2014); Prescott-Gagnon et al. (2014); Parragh and Cordeau (2017)
LB techniques	Mouro and Almeida (2000); Mouro and Amado (2005)
BPC	Rothenbächer et al. (2016)
	Heuristic
TS	Semet and Taillard (1993); Angelelli and Speranza (2002b,a); Chao (2002); De Rosa et al. (2002); Ghiani et al. (2004); Scheuerer (2006); Crevier et al. (2007); Tarantilis et al. (2008); Benjamin and Beasley (2010); Prescott-Gagnon et al. (2014)
(A)LNS	Buhrkal et al. (2012); Salazar-Aguilar et al. (2012); Derigs et al. (2013); Salazar-Aguilar et al. (2013); Schiffer et al. (2017b); Parragh and Cordeau (2017)
(A)VNS	Del Pia and Filippi (2006); Polacek et al. (2008); Tarantilis et al. (2008); Benjamin and Beasley (2010); Villegas et al. (2010, 2011); Hemmelmayr et al. (2013a,b); Prescott-Gagnon et al. (2014); Schneider et al. (2015); Markov et al. (2016)
LS	Gerdessen (1996); Del Pia and Filippi (2006); Tarantilis et al. (2008); Derigs et al. (2013); Hemmelmayr et al. (2013a); Markov et al. (2016); Schiffer et al. (2017b)
two-phase algorithm	Mouro and Almeida (2000); Ghiani et al. (2005); Kim et al. (2006); Coene et al. (2010); Amaya et al. (2010); Willemse and Joubert (2016)
path-scanning	Santos et al. (2008); Willemse and Joubert (2016)
EA	Tan et al. (2006); Ghiani et al. (2010)
Other	Beltrami and Bodin (1974); Jordan (1987); Ghiani et al. (2001); Mouro and Amado (2005); Crevier et al. (2007); Lin (2008); Santos et al. (2008); Villegas et al. (2010, 2011); Qu and Bard (2012)

Abbreviations hold as follows: (M)I(L)P - (mixed) integer (linear) program; BC - branch-and-cut; DP - dynamic programing; BP - branch-and-price; CG - column generation, LB - lower bound, BPC - branch-and-price-and-cut; TS - tabu search; (A)LNS - (adaptive) large neighborhood search; (A)VNS - (adaptive) variable neighborhood search; LS - local search; EA - evolutionary algorithms.

are metaheuristics, which is mainly due to the problem size of most application cases (cf. Tables 6 and 7). Note, that the listed MIPs are mostly used to provide a formal problem definition and not to solve the problem. Exact solution methods focus on the most promising approaches for routing problems (e.g., BP algorithms (Muter et al., 2014; Parragh and Cordeau, 2017; Prescott-Gagnon et al., 2014)). A first BPC algorithm for the TTRP was proposed by Rothenbächer et al. (2016). In addition, several metaheuristic algorithms incorporate dynamic programming components to optimally locate intermediate stops on routes (e.g., Hemmelmayr et al., 2013a; Schiffer et al., 2017b). As can be seen, TS and VNS are the most popular algorithms for this problem class. Contrary to other VRP variants, evolutionary algorithms, which turned out to be effective for a wide class of VRPs (cf. Vidal et al., 2012, 2013, 2014), are only rarely used.

Table 6 and Table 7 provide an overview of the benchmark sets that have been published for node routing (Table 6) and arc routing (Table 7) with intermediate stops for replenishment and unloading. The tables show the number of instances (I), as well as the number of nodes (N) or arcs (A), and the number of intra-route facilities (IF). As can be seen, some instance sets established as standard benchmark sets in the last years, while others have only been used by the authors themselves. For TTRPs, the benchmark sets of Chao (2002) and Lin (2008) are the most used. For VRPs with replenishment stops, this role is taken by the benchmark sets of Crevier et al. (2007) and Tarantilis et al. (2008). Especially large instance were developed by Benjamin and Beasley (2010) and Kim et al. (2006) from the case studies on waste collection.

Concluding, RPIS for unloading and transshipment represent the majority of problems in the analyzed application area, while problems focusing on intermediate stops for replenishing in classical logistics applications account for a share of only 20%. Both arc routing and node routing problems have been solved. While the first are often related to municipal services, the latter arise mostly in classical distribution services. However, uncertainties have not been considered so far. While neglecting uncertainties seems to be appropriate

Table 6: Instances for node routing problems with intermediate stops for replenishment or unloading.

Reference	Type	I	N	IF	Used within
Gerdessen (1996)	NIF	150	50–200	50–200	
Chao (2002)	NIF	21	50–199	13–150	Scheuerer (2006); Villegas et al. (2011); Derigs et al. (2013); Belenguer et al. (2016)
Angelelli and Speranza (2002b)	NIF	42	50–288	1–4	
Kim et al. (2006)	AIFTW	10	102–2100		
Crevier et al. (2007)	NIFMRD	22	48–288	3–7	Tarantilis et al. (2008); Hemmelmayr et al. (2013a); Muter et al. (2014); Schneider et al. (2015); Markov et al. (2016); Schiffer et al. (2017b)
Tarantilis et al. (2008)	NIFMRD	54	50–175	3–8	Hemmelmayr et al. (2013a); Schneider et al. (2015); Schiffer et al. (2017b)
Lin (2008)	NIF	30	50–100	50–100	Derigs et al. (2013); Parragh and Cordeau (2017)
Benjamin and Beasley (2010)	NIFMRD	10	99–2092	1–19	Buhrkal et al. (2012)
Qu and Bard (2012)	NIFTW	50	25	1	
Salazar-Aguilar et al. (2013)	AIF	60	200–350	60–100	
Drexl (2014)	NIFTW	109	16–106		Rothenbächer et al. (2016)
Prescott-Gagnon et al. (2014)	NIFTW	18	250–750		
Parragh and Cordeau (2017)	AIFTW	18	25–100	7–75	Rothenbächer et al. (2016)
Case studies		2	184–387	1–3	Hemmelmayr et al. (2013b); Markov et al. (2016)

If the number of intra-route facilities is not known, IF is left empty.

Table 7: Instances for arc routing problems with intermediate stops for replenishment or unloading.

Reference	Type	I	A	IF	Used within
Mouro and Almeida (2000)	AIF	30	13–97	1	
Ghiani et al. (2001)	AIF	51	11–97	1–2	Ghiani et al. (2004); Polacek et al. (2008); Ghiani et al. (2010)
De Rosa et al. (2002)	AIFMRD	59	19–97	1	
Mouro and Amado (2005)	AIF	30	94–743	1	
Amaya et al. (2007)	AIF	180	50–595	3–5	Amaya et al. (2010)
Salazar-Aguilar et al. (2012)	AIF	45	113–795		
Willemse and Joubert (2016)	NIFMRD	3	1012–2755	2	
Case studies		2	376–422		Ghiani et al. (2005); Del Pia and Filippi (2006)

If the number of intra-route facilities is not known, IF is left empty.

for some of the application cases (e.g., waste collection, road painting, small package shipping), considering uncertain demand in delivery problems with raw materials (e.g., propane distribution) or uncertain travel times in problem variants with time windows seems to constitute a promising research direction.

3 Intermediate stops for refueling

We now consider publications that focus on intermediate stops for refueling. Intermediate stops for refueling arise in both dense and sparse refueling infrastructures. While dense infrastructures exist for ICEV fleets, sparse infrastructures arise mainly for AFV fleets. Section 3.1 focuses on refueling stops in dense refueling infrastructure. Intermediate stops for sparse refueling infrastructures are discussed in Section 3.2. Section 3.3 addresses vehicle scheduling problems with intermediate stops for refueling. Finally, Section 3.4 concludes this discussion with a detailed analysis of problem variants and algorithms.

3.1 Intermediate stops for refueling in dense refueling networks

Routing problems with intermediate stops for refueling in dense refueling networks are relevant for ICEV fleets due to economic reasons, e.g., to take advantage of price differences at spatially close gas filling stations.

The first papers in this context were written by Ichimori and Ishii (1981) and Ichimori et al. (1983), focusing on a shortest path problem (SPP) for vehicles with limited fuel capacity and refueling options that are limited to dedicated nodes. The authors presented a modified Dijkstra algorithm to solve this problem. Suzuki (2008) provided an integer program for fuel stop optimization for truckload carriers. Although this approach is related to intermediate stops for refueling with dense infrastructure, it is not included in our detailed analysis because routes are predetermined and given. This problem was extended by determining not only the necessary stops but also the refueled quantity at each stop in Suzuki (2009). Bousonville et al. (2011) included refueling decisions for ICEVs into a VRPTW and analyzed the impact of price variations, especially on the tour length. The objective focused on minimizing the overall costs for refueling, and Solomon's I1 construction heuristic was applied. Khuller et al. (2011) studied SPPs and traveling salesman problems (TSPs) with price varying refueling options. Suzuki (2012) focused on a TSP with time windows and time-sensitive demand, considering refueling options. In addition, Suzuki and Dai (2012) proposed a variable reduction technique for this problem.

3.2 Intermediate stops for refueling in sparse refueling networks

Intermediate stops for refueling with sparse refueling structures arise mainly for ECVs and other AFVs. VRP variants, SPPs and TSPs, as well as location-routing problem (LRP) variants have been studied in this context.

Gonçalves et al. (2011) considered a VRP with pickups and deliveries and a mixed fleet of ICEVs and ECVs to study the integration of ECVs in the fleet of a battery distributor. The authors presented a MIP minimizing fixed vehicle costs and routing costs. Although recharging time for intermediate stops is considered, dedicated charging station vertices are not used. Conrad and Figliozzi (2011) introduced the recharging VRP in which vehicles with a limited driving range are allowed to recharge en route at certain customer locations, while considering a fixed recharging time and customer time windows. The authors used a lexicographic objective function to first minimize the number of vehicles and then the routing cost. Erdoğan and Miller-Hooks (2012) proposed the green VRP (GVRP) that considers a limited fuel capacity for AFVs and refueling options on routes, while restricting the maximum duration of a route. The authors proposed a modified savings algorithm (cf. Clarke and Wright, 1964) and a density based route-first cluster-second algorithm. Focusing on an airport shuttle service, Barco et al. (2013) presented a comprehensive approach for integrating ECVs into a fleet of shuttle vehicles. Schneider et al. (2014) were the first to address the electric VRP (EVRP) with time windows (EVRPTW) focusing on a pure electric vehicle fleet and dedicated vertices for recharging activities considering quantity-dependent recharging times.The authors also used the lexicographic objective function of Conrad and Figliozzi (2011).

Felipe et al. (2014) introduced the GVRP with multiple technologies and partial recharges (GVRPMTPR), focusing on different types of recharging stations for ECV and taking different costs, different charging speeds, and partial recharging into consideration. Sassi et al. (2015c) presented an EVRP with partial recharging and a heterogeneous ECV fleet, with a lexicographic objective function that first minimizes the number of vehicles and then the distance and charging cost. The same authors presented a multi-start iterated local search in Sassi et al. (2015b) and an iterated TS in Sassi et al. (2015a) for this problem. Goeke and Schneider (2015) analyzed an EVRP with a mixed fleet of ICEVs and ECVs, considering a realistic energy consumption function using data on vehicle speed, vehicle load, and gradients. Another EVRP that considers the impact of the vehicle load on the energy consumption was proposed by Lin et al. (2016). The authors minimized total costs and showed the relevance of considering the influence of load in a case study in Texas. Bruglieri et al. (2015a) and Bruglieri et al. (2015b) proposed a matheuristic based on a variable neighborhood branching for the EVRPTW. Montoya et al. (2016) developed a multi-space sampling heuristic for the GVRP. Verma et al. (2015) investigated the EVRPTW for battery swapping stations instead of recharging stations. The authors developed a VNS to solve this problem and calculated results on the instances of Schneider et al. (2014). Hiermann et al. (2016) investigated the EVRPTW with heterogeneous electric vehicles that yield different acquisition costs and vehicle-independent routing costs.

Desaulniers et al. (2016) developed a BPC algorithm for the EVRPTW, covering four variants with single and multiple recharge stops per route as well as full and partial recharging. The authors presented a mono-directional and a bi-directional pricing labeling algorithm and found that multiple recharges improve the overall solution with respect to the number of vehicles and costs. Keskin and Çatay (2016) addressed the EVRPTW and partial recharging (EVRPTWPR) and developed an ALNS. Koç and Karaoglan (2016) focused on the GVRP and introduced a BC algorithm to improve lower bounds and a simulated annealing (SA) algorithm to calculate upper bounds. Yavuz and apar (2017) discussed the adoption of AFVs in service fleets. Montoya et al. (2017) investigated an EVRP allowing for partial recharging and considering a non-linear charging function. The authors presented a hybrid algorithm based on VNS and LS. Additionally, they presented a component to insert charging stations into routes, either based on a greedy heuristic or on a mixed integer program. Yavuz (2017) proposed an iterated beam search algorithm for the GVRP. Schiffer et al. (2017a) introduced the EVRP with truck driver scheduling (EVRPTDS) and analyzed the impact of HOS regulations on the competitiveness of ECVs compared to ICEVs, synchronizing idle times for recharging and breaking. The authors presented an ALNS-based algorithm with a time-efficient HOS scheduling component and analyzed European Union (EU) as well as United States (US) HOS regulations.

The first publications on generic VRPIS variants only appeared recently. Schneider et al. (2015) developed a generalized VRPIS model and presented an adaptive VNS that provided good results on the GVRP and EVRP variants with full recharging options. Schiffer et al. (2017b) developed a generic algorithmic framework for VRPISs based on an ALNS with an additional DP element. This algorithm yields the best known results for several EVRP variants, namely the EVRPTW, the EVRPTWPR, and the EVRP with maximum route duration, and the GVRP.

Besides publications on VRP variants, SPPs and TSPs have been investigated. Liao et al. (2016) introduced the electric vehicle touring problem that accounts for a shortest route that can be chosen by an ECV to get from an origin to a destination. On this route, the ECV may stop at one or several battery swapping stations to switch its battery. The authors presented a polynomial-time algorithm for this problem. Roberti and Wen (2016) introduced the electric TSP with time windows and presented a three-phase heuristic based on a VNS and dynamic programming to solve instances with up to 200 customers. Further work on routing pure ECVs has been presented by Sweda et al. (2017), accounting for uncertain recharging options over time, so that adaptive routing and recharging decisions can be optimized. Further work on routing ECVs on energy shortest paths was presented by Artmeier et al. (2010b,a); Sachenbacher et al. (2011); Sweda and Klabjan (2012). However, these publications are not related to intermediate recharging stops.

The first papers focusing on hybrid electric vehicles (HEVs) were published only recently. Arslan et al. (2015) presented the minimum cost path problem for plug-in hybrid electric vehicles, considering refueling and recharging stations with different cost structures. The authors presented a dynamic programming and a shortest path algorithm, minimizing overall costs. Doppstadt et al. (2016) introduced the hybrid electric vehicle TSP in which vehicles can switch between different engine modes and presented a TS heuristic to solve large-sized instances. Another publication on hybrid electric vehicles was presented by Mancini (2017), who introduced the hybrid VRP in which vehicles can either switch their engine mode once the battery is discharged or can be recharged at specific charging stations. Nejad et al. (2017b) focused on optimal routing for plug-in hybrid electric vehicles and provided different exact DP-based algorithms for this problem.

The first publications on LRPs in the context of ECVs were also recently published. Because decisions on vehicle routing and charging station locations are interdependent, a simultaneous consideration bears a significant improvement potential at strategic level (cf. Schiffer and Walther, 2017b). These publications are a variant of the LRP with intra-route facilities (LRPIF) (cf. Schiffer and Walther, 2017a). The LRPIF differs from conventional LRPs because the decision is on locating intra-route facilities as introduced in Section 1 instead of depots. In the following, we focus on LRPIF variants and refer to recent surveys (Lopes et al., 2013; Drexl and Schneider, 2014; Schneider and Drexl, 2017; Prodhon and Prins, 2014; Cuda et al., 2015; Albareda-Sambola, 2015) for an overview of conventional LRPs.

The first LRP in this context is by Yang and Sun (2015) who introduced the battery swap station electric vehicle LRP (BSS-EV-LRP) that simultaneously determines battery swapping station locations and vehicle routes. Hof et al. (2017) extended the VNS developed in Schneider et al. (2015) to the BSS-EV-LRP and significantly improved the results of Yang and Sun (2015). Schiffer and Walther (2017b) introduced the electric LRP with time windows and partial recharging (ELRPTWPR), which extends the BSS-EV-LRP to a more general problem formulation, accounting for partial recharging, time windows and time-dependent recharging. The authors discussed different objective functions and highlighted the impact of simultaneous charging station location and vehicle routing decisions. Schiffer et al. (2016) presented a case study for the ELRPTWPR based on the distribution network of a German retail company and showed that ECVs are on the verge of breaking even for certain application cases. Since customer patterns heavily affect the routing and the interdependent charging station location decision, Schiffer and Walther (2017c) introduced a robust ELRPTWPR that considers uncertainty in customer patterns with regard to the spatial distribution, demand and time windows. The authors presented a parallelized ALNS to solve this problem. In a more generic fashion, Schiffer and Walther (2017a) introduced the LRPIF which is not limited to ECVs and charging stations but also accounts for conventional vehicles or other AFVs and intra-route facilities for freight replenishment. The authors presented new benchmark instances and an ALNS with a DP component. Schiffer et al. (2017c) extended the LRPIF for combined facilities at which recharging energy and replenishing freight can take place simultaneously. Furthermore, the authors integrated lower bounding techniques to avoid unpromising facility configurations in an ALNS. This algorithm yields the best results for all LRPIF variants discussed above.

3.3 Scheduling of vehicles with limited driving range

Electric vehicle scheduling problems (EVSPs) constitute a related problem class to RPISs for refueling. Even if routes are predetermined (e.g., for electric buses), scheduling recharging stops on these routes is necessary due to the vehicles' limited driving range. Since this research stream is a related problem class, we provide a concise overview on recent publications for the sake of completeness, but exclude these publications from our detailed analysis in Section 3.4 because the routing decision is missing.

Li (2014) were the first to study the EVSP in the course of transit bus scheduling with limited energy. The authors developed CG based algorithms and presented results for real-world data. Sassi and Oulamara (2014, 2017) considered the EVSP on an abstract level and presented an iterative MIP and a sequential heuristic solution approach. Wen et al. (2016) focused on the EVSP in the context of electric bus scheduling considering partial charging. The authors presented a MIP and an ALNS algorithm for large-scale instances. Adler and Mirchandani (2017) investigated vehicle scheduling for alternative fuel vehicles in general and presented a BP algorithm. Nejad et al. (2017a) focused on optimal electric vehicle charging scheduling by integrating price interests of users and power providers. Wang et al. (2017) presented a case study for the EVSP for urban electric buses in Davis, California.

3.4 Analysis of intermediate stops for refueling

The following detailed analysis is limited to the publications listed in Sections 3.1 and 3.2. Table 8 summarizes the scope of these publications. Besides *i*) the type of publication and *ii*) the type of the routing problem, which have also been discussed for Section 2, we include additional characteristics. We further differentiate between *iii*) the vehicle type, *iv*) the type of data (as in Section 2), *v*) the modeling approach, and *vi*) the refueling infrastructure. As can be seen in Figure 5, the share of publications that describe case studies is rather low (18%), while most publications focus on methodological improvements (82%). Problems on intermediate stops for refueling are mostly tackled as pure routing problems (84%) (TSP/SPP, VRP); a

Table 8: Scope of publications on intermediate stops for refueling.

Case Study	Gonçalves et al. (2011); Barco et al. (2013); Lin et al. (2016); Sassi et al. (2015c); Schiffer et al. (2016); Yavuz and apar (2017); Nejad et al. (2017b); Schiffer et al. (2017a)
Methodological	Ichimori and Ishii (1981); Ichimori et al. (1983); Bousonville et al. (2011); Conrad and Figliozzi (2011); Khuller et al. (2011); Erdoğan and Miller-Hooks (2012); Suzuki (2012); Felipe et al. (2014); Hiermann et al. (2016); Schneider et al. (2014); Arslan et al. (2015); Bruglieri et al. (2015b,a); Goeke and Schneider (2015); Mancini (2017); Montoya et al. (2016, 2017); Sassi et al. (2015a,b); Schiffer and Walther (2017b); Schneider et al. (2015); Verma et al. (2015); Yang and Sun (2015); Desaulniers et al. (2016); Doppstadt et al. (2016); Keskin and Çatay (2016); Koç and Karaoglan (2016); Roberti and Wen (2016); Schiffer and Walther (2017a); Schiffer et al. (2017b); Sweda et al. (2017); Hof et al. (2017); Schiffer and Walther (2017c); Schiffer et al. (2017c); Yavuz (2017)
Node routing	Bousonville et al. (2011); Conrad and Figliozzi (2011); Gonçalves et al. (2011); Khuller et al. (2011); Erdoğan and Miller-Hooks (2012); Suzuki (2012); Barco et al. (2013); Felipe et al. (2014); Hiermann et al. (2016); Schneider et al. (2014); Bruglieri et al. (2015b,a); Goeke and Schneider (2015); Lin et al. (2016); Mancini (2017); Montoya et al. (2016, 2017); Sassi et al. (2015c,a,b); Schiffer and Walther (2017b); Schneider et al. (2015); Verma et al. (2015); Yang and Sun (2015); Desaulniers et al. (2016); Doppstadt et al. (2016); Keskin and Çatay (2016); Koç and Karaoglan (2016); Roberti and Wen (2016); Schiffer and Walther (2017a); Schiffer et al. (2017b, 2016); Yavuz and apar (2017); Hof et al. (2017); Schiffer and Walther (2017c); Schiffer et al. (2017c,a); Yavuz (2017)
Arc routing	Ichimori and Ishii (1981); Ichimori et al. (1983); Khuller et al. (2011); Arslan et al. (2015); Sweda et al. (2017); Nejad et al. (2017b)
ECV	Conrad and Figliozzi (2011); Gonçalves et al. (2011); Barco et al. (2013); Felipe et al. (2014); Hiermann et al. (2016); Schneider et al. (2014); Bruglieri et al. (2015b,a); Goeke and Schneider (2015); Lin et al. (2016); Montoya et al. (2017); Sassi et al. (2015c,a,b); Schiffer and Walther (2017b); Schneider et al. (2015); Verma et al. (2015); Yang and Sun (2015); Desaulniers et al. (2016); Keskin and Çatay (2016); Koç and Karaoglan (2016); Roberti and Wen (2016); Schiffer and Walther (2017a); Schiffer et al. (2017b, 2016); Sweda et al. (2017); Hof et al. (2017); Schiffer and Walther (2017c); Schiffer et al. (2017c,a)
HEV	Arslan et al. (2015); Mancini (2017); Doppstadt et al. (2016); Nejad et al. (2017b)
ICEV	Ichimori and Ishii (1981); Ichimori et al. (1983); Bousonville et al. (2011); Khuller et al. (2011); Suzuki (2012)
AFV	Erdoğan and Miller-Hooks (2012); Montoya et al. (2016); Schneider et al. (2015); Schiffer et al. (2017b); Yavuz and apar (2017); Yavuz (2017)
Deterministic	Bousonville et al. (2011); Conrad and Figliozzi (2011); Gonçalves et al. (2011); Khuller et al. (2011); Erdoğan and Miller-Hooks (2012); Suzuki (2012); Barco et al. (2013); Felipe et al. (2014); Hiermann et al. (2016); Schneider et al. (2014); Bruglieri et al. (2015b,a); Goeke and Schneider (2015); Lin et al. (2016); Mancini (2017); Montoya et al. (2016, 2017); Sassi et al. (2015c,a,b); Schiffer and Walther (2017b); Verma et al. (2015); Yang and Sun (2015); Desaulniers et al. (2016); Doppstadt et al. (2016); Keskin and Çatay (2016); Koç and Karaoglan (2016); Roberti and Wen (2016); Schiffer and Walther (2017a); Schiffer et al. (2017b, 2016); Yavuz and apar (2017); Hof et al. (2017); Nejad et al. (2017b); Schiffer et al. (2017c,a); Yavuz (2017)
Uncertain	Sweda et al. (2017); Schiffer and Walther (2017c)
TSP / SPP	Ichimori and Ishii (1981); Ichimori et al. (1983); Khuller et al. (2011); Suzuki (2012); Arslan et al. (2015); Doppstadt et al. (2016); Roberti and Wen (2016); Sweda et al. (2017); Nejad et al. (2017b)
VRP	Bousonville et al. (2011); Conrad and Figliozzi (2011); Gonçalves et al. (2011); Erdoğan and Miller-Hooks (2012); Barco et al. (2013); Felipe et al. (2014); Hiermann et al. (2016); Schneider et al. (2014); Bruglieri et al. (2015b,a); Goeke and Schneider (2015); Lin et al. (2016); Mancini (2017); Montoya et al. (2016, 2017); Sassi et al. (2015c,a,b); Schneider et al. (2015); Verma et al. (2015); Desaulniers et al. (2016); Keskin and Çatay (2016); Koç and Karaoglan (2016); Schiffer et al. (2017b); Yavuz and apar (2017); Schiffer et al. (2017a); Yavuz (2017)
LRP	Schiffer and Walther (2017b); Yang and Sun (2015); Schiffer and Walther (2017a); Schiffer et al. (2016); Hof et al. (2017); Schiffer and Walther (2017c); Schiffer et al. (2017c)
Dense	Ichimori and Ishii (1981); Ichimori et al. (1983); Bousonville et al. (2011); Khuller et al. (2011); Suzuki (2012)
Sparse	Gonçalves et al. (2011); Conrad and Figliozzi (2011); Erdoğan and Miller-Hooks (2012); Barco et al. (2013); Schneider et al. (2014); Felipe et al. (2014); Sassi et al. (2015c,a,b); Goeke and Schneider (2015); Bruglieri et al. (2015b,a); Lin et al. (2016); Montoya et al. (2016); Schneider et al. (2015); Verma et al. (2015); Hiermann et al. (2016); Desaulniers et al. (2016); Keskin and Çatay (2016); Koç and Karaoglan (2016); Doppstadt et al. (2016); Roberti and Wen (2016); Yavuz and apar (2017); Mancini (2017); Montoya et al. (2017); Nejad et al. (2017b); Sweda et al. (2017); Yavuz (2017); Schiffer and Walther (2017b); Yang and Sun (2015); Schiffer and Walther (2017a); Schiffer et al. (2016); Hof et al. (2017); Schiffer and Walther (2017c); Schiffer et al. (2017c,a,b); Arslan et al. (2015)

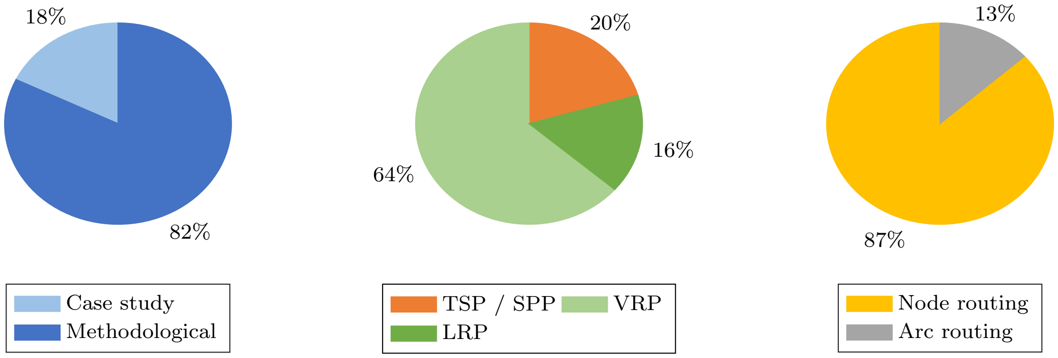

Figure 5: Characteristics of publications on intermediate stops for refueling.

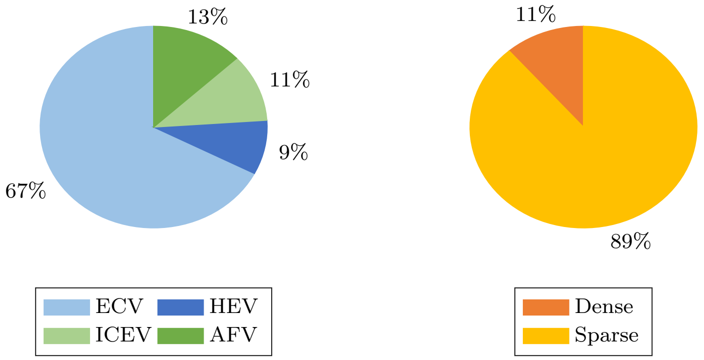

Figure 6: Characteristics of publications on intermediate stops for refueling.

much smaller proportion (16%) also considers the location component. Most publications consider node routing problems (87%), whereas only 13% cover arc routing problems. While the first are related to logistics fleets, the latter are related to routing algorithms for navigation systems or SPPs. The large majority of publications focuses on ECVs (67%), while only a limited number of publications focus on HEVs (9%) or on AFVs (13%) (cf. Figure 6). Only 11% consider ICEVs. This corresponds to the proportion of problems in which a dense refueling structure is considered (11%), while all publications that are related to any kind of AFVs consider a sparse refueling structure.

Figure 7 and Table 9 detail the problem types, based on the definition given in Table 1. Because all problems focus on fuel or energy that is consumed while driving, they are all arc-based. Considering the time restrictions, all possible characteristics are addressed. The majority of the problems considers time-dependent replenishment processes (57%), and time window restrictions are also considered (46%). Overall, 78% of the problems include time constraints. Furthermore, the models analyzed in this section are the only ones that account for partial replenishment because refueling consumes a significant amount of time for ECVs.

Figure 8 and Table 10 illustrate the different objective functions. As can be seen, most publications minimize overall costs or the total driven distance. Some publications make use of the lexicographic objective function approach used in heuristics on the classical VRPTW, minimizing the number of vehicles first and the total traveled distance second. Other objectives, e.g., minimizing the overall duration or consumed energy are only rarely applied.

Table 11 shows the different algorithms that have been used to solve routing problems with refueling stops. A majority of the problems use a MIP to define the analyzed problem in a formal way but not to create solutions on large-sized instances. Again, metaheuristics are more often used than exact algorithms. The few available exact algorithms are based on BP, BC, and BPC. Only for SPPs, a few polynomial time algorithms have been presented (e.g., Sweda et al. (2017)). Metaheuristics mainly use ALNS and VNS.

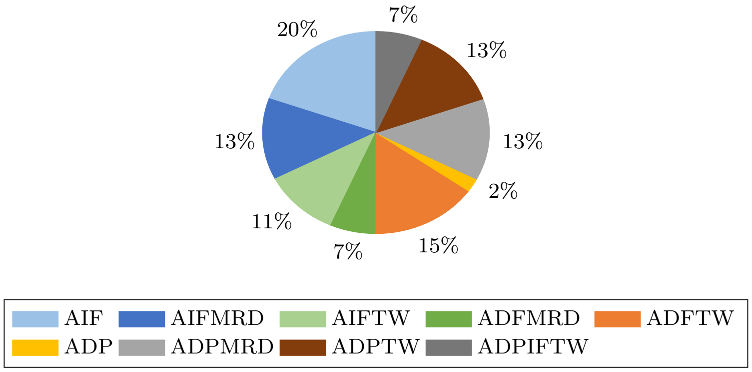

Figure 7: Types of problem variants for intermediate stops for refueling.

Table 9: Types of problem variants for intermediate stops for refueling.

AIF	Ichimori and Ishii (1981); Ichimori et al. (1983); Khuller et al. (2011); Arslan et al. (2015); Yang and Sun (2015); Doppstadt et al. (2016); Liao et al. (2016); Hof et al. (2017); Nejad et al. (2017b)
AIFMRD	Gonçalves et al. (2011); Erdoğan and Miller-Hooks (2012); Montoya et al. (2016); Schneider et al. (2015); Koç and Karaoglan (2016); Yavuz (2017)
AIFTW	Bousonville et al. (2011); Conrad and Figliozzi (2011); Suzuki (2012); Barco et al. (2013); Verma et al. (2015)
ADFMRD	Lin et al. (2016); Mancini (2017); Schneider et al. (2015)
ADFTW	Hiermann et al. (2016); Schneider et al. (2014); Bruglieri et al. (2015a,b); Goeke and Schneider (2015); Schneider et al. (2015); Desaulniers et al. (2016)
ADP	Sweda et al. (2017)
ADPMRD	Felipe et al. (2014); Montoya et al. (2017); Sassi et al. (2015c,a,b); Yavuz and apar (2017)
ADPTW	Schiffer and Walther (2017b); Desaulniers et al. (2016); Keskin and Çatay (2016); Roberti and Wen (2016); Schiffer and Walther (2017a); Schiffer et al. (2016)
ADPIFTW	Schiffer et al. (2017c,a)

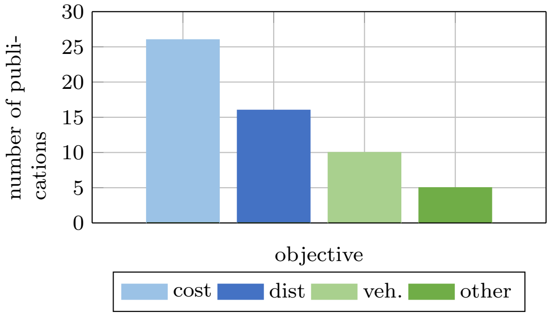

Figure 8: Objectives for intermediate stops for refueling.

Table 10: Objectives for intermediate stops for refueling.

Objective	References
Costs	Bousonville et al. (2011); Conrad and Figliozzi (2011); Gonçalves et al. (2011); Khuller et al. (2011); Suzuki (2012); Felipe et al. (2014); Hiermann et al. (2016); Arslan et al. (2015); Goeke and Schneider (2015); Lin et al. (2016); Sassi et al. (2015c,a,b); Schiffer and Walther (2017b); Verma et al. (2015); Yang and Sun (2015); Desaulniers et al. (2016); Doppstadt et al. (2016); Schiffer and Walther (2017a); Schiffer et al. (2016); Sweda et al. (2017); Yavuz and apar (2017); Hof et al. (2017); Schiffer et al. (2017c,a)
Distance	Ichimori and Ishii (1981); Ichimori et al. (1983); Erdoğan and Miller-Hooks (2012); Schneider et al. (2014); Bruglieri et al. (2015b,a); Mancini (2017); Montoya et al. (2016); Schiffer and Walther (2017b); Schneider et al. (2015); Keskin and Çatay (2016); Koç and Karaoglan (2016); Liao et al. (2016); Roberti and Wen (2016); Yavuz and apar (2017); Yavuz (2017)
duration	Montoya et al. (2017)
Num. Veh. / trips	Conrad and Figliozzi (2011); Schneider et al. (2014); Bruglieri et al. (2015b,a); Sassi et al. (2015c,a,b); Schiffer and Walther (2017b); Schneider et al. (2015); Keskin and Çatay (2016)
Energy	Barco et al. (2013); Nejad et al. (2017b)
Emissions	Yavuz and apar (2017)
Num. stations	Schiffer and Walther (2017b)

Contrary to problems with intermediate stops for unloading or replenishment, TS is only rarely used.

Table 12 summarizes the instance sets published so far. Three benchmark sets are used regularly to assess the competitiveness of algorithms. For the GVRP, there are the instance sets of Erdoğan and Miller-Hooks (2012), while the instance sets of Schneider et al. (2014) are used for EVRP variants. In a location-routing context, the instance set of Yang and Sun (2015) is used to assess the competitiveness of LRPIF algorithms.

Table 11: Solution methods.

	Exact
(M)I(L)P	Conrad and Figliozzi (2011); Gonçalves et al. (2011); Erdoğan and Miller-Hooks (2012); Felipe et al. (2014); Schneider et al. (2014); Bruglieri et al. (2015b,a); Goeke and Schneider (2015); Lin et al. (2016); Mancini (2017); Montoya et al. (2017); Sassi et al. (2015c); Schiffer and Walther (2017b); Schneider et al. (2015); Doppstadt et al. (2016); Liao et al. (2016); Schiffer et al. (2016); Schiffer and Walther (2017c)
B&P / CG	Hiermann et al. (2016); Montoya et al. (2016)
DP	Arslan et al. (2015); Roberti and Wen (2016); Schiffer and Walther (2017a); Schiffer et al. (2017b, 2016); Nejad et al. (2017b); Schiffer and Walther (2017c)
B&C	Koç and Karaoglan (2016)
B&P&C	Desaulniers et al. (2016)
Other	Ichimori and Ishii (1981); Ichimori et al. (1983); Khuller et al. (2011); Liao et al. (2016); Sweda et al. (2017); Yavuz (2017)
	Heuristic
TS	Schneider et al. (2014); Sassi et al. (2015a); Doppstadt et al. (2016)
(A)LNS	Hiermann et al. (2016); Goeke and Schneider (2015); Mancini (2017); Yang and Sun (2015); Keskin and Çatay (2016); Schiffer and Walther (2017a); Schiffer et al. (2017b, 2016); Schiffer and Walther (2017c); Schiffer et al. (2017c,a)
(A)VNS	Schneider et al. (2014); Bruglieri et al. (2015b,a); Montoya et al. (2017); Schneider et al. (2015); Verma et al. (2015); Roberti and Wen (2016); Yavuz and apar (2017); Hof et al. (2017)
LS	Felipe et al. (2014); Hiermann et al. (2016); Goeke and Schneider (2015); Montoya et al. (2017); Sassi et al. (2015c,b); Schneider et al. (2015); Verma et al. (2015); Schiffer and Walther (2017a); Schiffer et al. (2017b, 2016); Hof et al. (2017); Schiffer and Walther (2017c); Schiffer et al. (2017c,a)
SA	Suzuki (2012); Felipe et al. (2014); Goeke and Schneider (2015); Koç and Karaoglan (2016)
two-phase algorithm	Erdoğan and Miller-Hooks (2012); Montoya et al. (2016)
other	Bousonville et al. (2011); Conrad and Figliozzi (2011); Barco et al. (2013); Arslan et al. (2015); Sweda et al. (2017)

Abbreviations hold as follows: (M)I(L)P - (mixed) integer (linear) program; B&C - branch-and-cut; DP - dynamic programing; B&P - branch-and-price; CG - column generation, LB - lower bound, B&P&C - branch-and-price-and-cut; TS - tabu search; (A)LNS - (adaptive) large neighborhood search; (A)VNS - (adaptive) variable neighborhood search; LS - local search; SA - simulated annealing.

Table 12: Instance sets for routing problems with intermediate stops for refueling.

reference	Type	I	N	IF	Used within
Conrad and Figliozzi (2011)	AIF	30	40		
Bousonville et al. (2011)	AIFTW	56	100	121-441	
Suzuki (2012)	AIFTW	6	10–20	10–20	
Erdoğan and Miller-Hooks (2012)	AIFMRD	52	20–500	21–28	Felipe et al. (2014); Mancini (2017); Montoya et al. (2016); Koç and Karaoglan (2016); Schiffer et al. (2017b)
Felipe et al. (2014)	ADPMRD	60	100–400	5–9	
Schneider et al. (2014)	ADFTW	92	5–100	21	Felipe et al. (2014); Hiermann et al. (2016); Bruglieri et al. (2015a,b); Schiffer and Walther (2017b); Verma et al. (2015); Desaulniers et al. (2016); Keskin and Çatay (2016); Schiffer and Walther (2017a); Schiffer et al. (2017b)
Schneider et al. (2015)	ADFMRD	180	10–200	1–20	
Doppstadt et al. (2016)	AIF	36	8–50		
Roberti and Wen (2016)	ADPTW	100	20–200	5–10	
Yavuz and apar (2017)	ADPMRD	190	20–80	0–4	
Mancini (2017)		9	30–75	5–20	
Montoya et al. (2017)	ADPMRD	120	10–320	2–38	
Yang and Sun (2015)	AIF	24	16–480	det	Schiffer and Walther (2017a); Hof et al. (2017); Schiffer et al. (2017c)
Schiffer and Walther (2017c)	ADPTW	90	100	det	
Schiffer and Walther (2017a)	ADPTW	24	18–160	det	
Schiffer et al. (2017a)	ADPIFTW	56	100	897	
Schiffer et al. (2017c)	ADPIFTW	56	100	det	

If the number of intra-route facilities is not known or determined in an LRPIF, IF is left empty.

Concluding, most publications on intermediate stops for refueling focus on recharging stops for ECVs, which is a highly relevant topic with benefits for sustainable transport developments, e.g., by reducing range anxiety concerns (Pelletier et al., 2017). Most contributions focus on algorithmic aspects or extend existing EVRP variants by additional real-world constraints (e.g., realistic energy consumption, non-linear recharging). However, publications on case studies and real-world problems are quite sparse, which may be due to the fact that the adoption rate of ECVs is still quite low, and the expected market uptake is slow due to the concerns of practitioners. Thus, case studies that help to highlight the competitiveness of ECVs (e.g., Schiffer et al., 2016) and to reduce the concerns of practitioners on applicability or range anxiety seem to be an important research direction that, besides scientific contribution, adds societal value by boosting the market uptake of ECVs.

4 Intermediate stops for break and rest periods

The third field in which intermediate stops are required are routing problems that consider break and rest periods arising from HOS regulations or multi-day planning problems. The relevant literature can be classified into truck driver scheduling problems (TDSPs) that account for HOS regulations to which logistics fleets have to abide, and into team orienteering problems (TOPs) and TSPs with hotel selection that originated from trip planning in tourism. TDSPs can be further separated into classical TDSPs in which route plans are already fixed and only a break and rest sequence have to be scheduled on the routes, and vehicle routing and truck driver scheduling problems (VRTDSPs), in which route plans as well as break schedules are determined. Due to prefixed route plans, TDSPs do not fully match the scope of our survey. Thus, we only provide a brief overview of these problems in Section 4.1 but exclude these publications from our detailed analysis. Section 4.2 then gives an overview of VRTDSPs, and Section 4.3 focuses on TOPs and TSPs with hotel selection. In Section 4.4, we again analyze the characteristics of the considered publications.

4.1 Truck driver scheduling problems

Archetti and Savelsbergh (2009) were the first to focus on the TDSP by sequencing full truck load requests within an origin dispatch window. They presented a polynomial-complexity exact algorithm. Various HOS regulations have been studied by Goel and coauthors. Goel (2012b) focused on the TDSP under US and EU HOS regulations. This approach was extended for multiple time windows in Goel and Kok (2012). Goel and Rousseau (2012) discussed HOS regulations in Canada and discussed the minimum tour duration TDSP to these HOS in Goel (2012a). Goel (2012c) and Goel et al. (2012) focused on truck driver schedules in Australia. Motivated by vehicle idling options for heating purposes in winter long-haul trucking, Koç et al. (2016) introduced the TDSP with idling options (TDSPIO). The authors analyzed different idling options (e.g., stopping at an electrified parking space or using an auxiliary power unit) to keep the vehicle at an adequate comfort level during rests.

4.2 Vehicle routing problems with truck driver scheduling

The first publication of a VRP focusing on HOS is by Xu et al. (2003). The authors investigated a pickup and delivery VRP minimizing a cost objective that contains fixed, mileage and layover costs and paid special attention to additional real-world constraints, e.g., driver work rules. A CG based heuristic and lower bounding procedures were proposed to solve the problem. Ceselli et al. (2009) investigated another rich VRP with driver work rules, time windows and additional customer and freight restrictions. The authors presented a BP algorithm with a bidirectional labeling that solves the underlying pricing problem as an elementary shortest path problem. In a more methodological fashion, Goel (2009) introduced the VRTDSP by extending the standard VRPTW to HOS regulations. This work focused on the EU HOS regulations and applied a LNS heuristic. The author minimized the number of vehicles as first and the overall traveled distance as a secondary objective. Benchmark instances were created based on the VRPTW instances of Solomon (1987). Further work on integrating EU HOS regulations into the VRPTW was published by Kok et al. (2010). Besides basic HOS regulations that have already been addressed in Goel (2009), the authors considered additional regulations that allow for more flexibility by adding small exceptions to the daily driving time. A restricted DP heuristic was presented and was shown to outperform the algorithm of Goel (2009). The authors found that slight modifications of HOS rules yield a significant decrease for both, the number of vehicles and the driven distance. Another contribution on the VRPTW with EU HOS regulations was published by Prescott-Gagnon et al. (2010). The authors presented an LNS-based CG heuristic that clearly outperformed the algorithms of Goel (2009) and Kok et al. (2010). Kok et al. (2011) developed a sequential insertion heuristic, focusing on the VRPTW with HOS regulations minimizing the route duration to keep some flexibility in case of traffic congestion. Results are discussed for a real-world case as well as for the Solomon benchmark instances. Rancourt et al. (2013) focused on US HOS regulations, considering a heterogeneous fleet and multiple time windows. The authors developed a unified TS algorithm with heuristic scheduling approaches for assigning breaks. Besides benchmark instances based on the Solomon instances, the authors analyzed a real-world case. An algorithmic framework based on a hybrid genetic search was proposed by Goel and Vidal (2014), considering EU, US, Australian and Canadian HOS regulations. The authors investigated the impact of different HOS with respect to safety and economic efficiency in this context. The first exact algorithm for the VRTDSP was proposed by Goel and Irnich (2016), introducing a BP algorithm for EU and US HOS regulations. A bidirectional dynamic programming approach was applied to solve the pricing problem as an elementary shortest path problem. Koç et al. (2017) introduced the VRTDSP with idling options (VRTDSPIO), considering idling costs beside routing and driver costs. The authors presented a matheuristic combining ALNS with a MIP and showed results on the Solomon benchmark sets. Schiffer et al. (2017a) introduced the EVRPTDS and analyzed the impact of HOS on the competitiveness of ECVs compared to ICEVs. The authors focused on EU as well as US HOS regulations and presented an ALNS as well as new real-world based benchmark instances.

4.3 Orienteering and traveling salesman problems with hotel selection

The TOP is also known as the selective TSP (cf. Laporte and Martello, 1990; Gendreau et al., 1998). Within the TOP, a circle of maximum profit has to be determined on a weighted graph with profits associated vertices, while this circle is not allowed to exceed a maximum distance or duration. The TOP is often applied to determine tourist trips or for traveling salespersons with limited time budgets. If multi-day trips are considered, hotel selection arises within TOPs as an idling variant. In the following, we analyze TOPs and TSPs with hotel selection and refer to Vansteenwegen et al. (2011) for a profound overview on TOPs in general.

Vansteenwegen et al. (2012) introduced the TSP with hotel selection and developed a LS heuristic and two constructive procedures. The authors investigated a lexicographic objective function, minimizing the number of trips first and the traveled distance second. New benchmark sets were proposed and used to show the effectiveness of the presented algorithm. Li and Keskin (2014) focused on the patrol coverage for state troopers and developed an LRP that can also be handled as a TOP with hotel selection (TOPHS). The authors developed a SA heuristic and designed instances based on the crash history data in Alabama. Castro et al. (2013) developed a memetic algorithm with a TS component for the TSP with hotel selection. This algorithm strongly outperforms the LS of Vansteenwegen et al. (2012). Divsalar et al. (2013) developed a VNS with an LS component for the orienteering problem with hotel selection. The authors created a large benchmark set of 224 instances to evaluate the performance of their algorithm. Divsalar et al. (2014b) proposed a memetic algorithm which clearly outperforms all other approaches on these benchmark instances. In addition, the authors developed 176 additional large-sized instances. This algorithm was also used in Divsalar et al. (2014a) to derive personalized multi-day trips in touristic regions. Baltz et al. (2015) studied the TSP with hotel selection and multiple time windows, proposing a cheapest insertion heuristic. The authors evaluated the algorithm on existing benchmark instances and used the algorithm to investigate an additional real-world case.

4.4 Analysis

In the following, we analyze all publications summarized in Section 4.2 and Section 4.3 while focusing on their most important characteristics.

Table 13 and Figure 9 highlight the scope of these publications. As can be seen, 37% of the publications focus on case studies, while 63% of the publications focus on a methodological contribution by introducing a new problem or a new algorithm for a certain problem class. All of the analyzed publications are based on a node routing problem formulation due to the addressed application areas (logistics fleets and trips with special points of interest). None of the analyzed publications considers uncertain data. All papers that consider HOS regulations are based on a VRP approach (63%) because logistics fleets are analyzed (cf. Figure 9). All approaches that focus on other application cases than logistics fleets are modeled as a TSP or TOP.

Figure 10 and Table 14 detail the shares of the different problem variants arising in the context of intermediate stops for idling. As time is the operational resource related to those stops, all problem variants are arc-based. Most papers consider a maximum route duration (42%) or time windows (42%), which arise out of a long-haul logistics context or a maximum trip duration for e.g., tourist trips. The problem variant ADPIFTW belongs to the EVRPTDS as discussed in Schiffer et al. (2017a) which is the only variant that addresses a goal conflict between two operational resources (driver time and energy).

Table 13: Scope of publications on intermediate stops for rests and breaks.

Case study	Ceselli et al. (2009); Kok et al. (2011); Rancourt et al. (2013); Divsalar et al. (2014a); Li and Keskin (2014); Baltz et al. (2015); Schiffer et al. (2017a)
Methodological	Xu et al. (2003); Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Vansteenwegen et al. (2012); Castro et al. (2013); Divsalar et al. (2013, 2014b); Goel and Vidal (2014); Goel and Irnich (2016); Koç et al. (2017)
Node routing	Xu et al. (2003); Ceselli et al. (2009); Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Kok et al. (2011); Vansteenwegen et al. (2012); Castro et al. (2013); Divsalar et al. (2013); Rancourt et al. (2013); Divsalar et al. (2014b,a); Goel and Vidal (2014); Li and Keskin (2014); Baltz et al. (2015); Goel and Irnich (2016); Koç et al. (2017); Schiffer et al. (2017a)
Arc routing	none
HOS regulations	Xu et al. (2003); Ceselli et al. (2009); Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Kok et al. (2011); Rancourt et al. (2013); Goel and Vidal (2014); Goel and Irnich (2016); Koç et al. (2017); Schiffer et al. (2017a)
Other	Vansteenwegen et al. (2012); Castro et al. (2013); Divsalar et al. (2013, 2014b,a); Li and Keskin (2014); Baltz et al. (2015)
Deterministic	Xu et al. (2003); Ceselli et al. (2009); Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Kok et al. (2011); Rancourt et al. (2013); Goel and Vidal (2014); Goel and Irnich (2016); Koç et al. (2017); Vansteenwegen et al. (2012); Castro et al. (2013); Divsalar et al. (2013, 2014b,a); Li and Keskin (2014); Baltz et al. (2015); Schiffer et al. (2017a)
Uncertain	none
VRP	Xu et al. (2003); Ceselli et al. (2009); Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Kok et al. (2011); Rancourt et al. (2013); Goel and Vidal (2014); Goel and Irnich (2016); Koç et al. (2017); Schiffer et al. (2017a)
TSP / TOP	Vansteenwegen et al. (2012); Castro et al. (2013); Divsalar et al. (2013, 2014b,a); Li and Keskin (2014); Baltz et al. (2015)

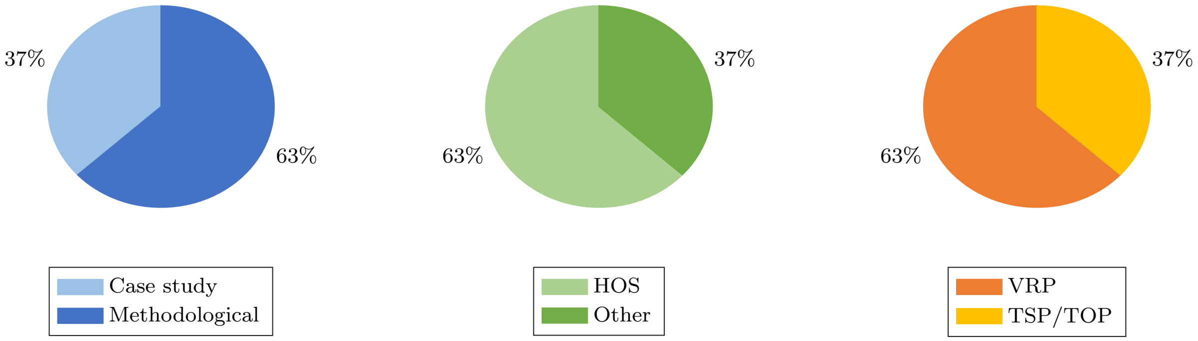

Figure 9: Characteristics of publications on intermediate stops for rests and breaks.

Figure 11 and Table 15 detail the objectives. While approximately 50% of the publications focus on a cost or duration minimization, there are also many papers that use a lexicographic objective, minimizing the number of vehicles first and the total distance second. These publications often focus on the VRTDSP. Only the TOP variants maximize the score of a trip.

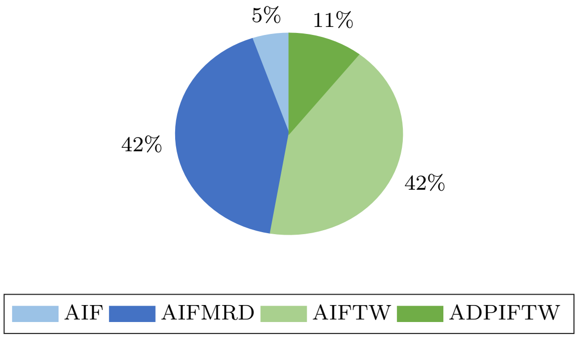

Figure 10: Types of problem variants for intermediate stops for rests and breaks.

Table 14: Types of problem variants for intermediate stops for rests and breaks.

AIF	Xu et al. (2003)
AIFMRD	Ceselli et al. (2009); Vansteenwegen et al. (2012); Castro et al. (2013); Divsalar et al. (2013, 2014b,a); Baltz et al. (2015); Koç et al. (2017)
AIFTW	Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Kok et al. (2011); Rancourt et al. (2013); Goel and Vidal (2014); Li and Keskin (2014); Goel and Irnich (2016)
ADPIFTW	Schiffer et al. (2017a)

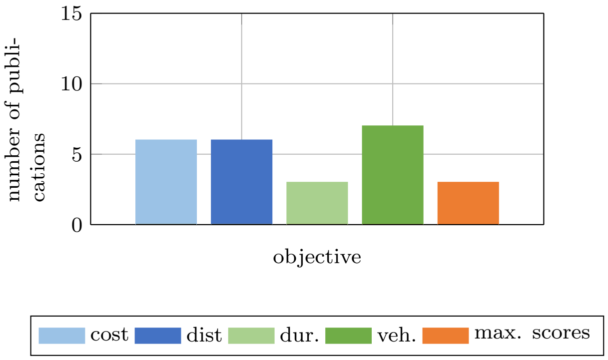

Figure 11: Objectives for intermediate stops for for break and rest periods.

Table 15: Objectives for intermediate stops for break and rest periods.

Objective	References
Costs	Xu et al. (2003); Ceselli et al. (2009); Baltz et al. (2015); Goel and Irnich (2016); Schiffer et al. (2017a)
Distance	Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Vansteenwegen et al. (2012); Castro et al. (2013); Goel and Vidal (2014)
Duration	Kok et al. (2011); Rancourt et al. (2013); Li and Keskin (2014)
Num. veh. / trips	Goel (2009); Kok et al. (2010); Prescott-Gagnon et al. (2010); Vansteenwegen et al. (2012); Castro et al. (2013); Rancourt et al. (2013); Goel and Vidal (2014)
Maximum scores.	Divsalar et al. (2013, 2014b,a)

The solution methods listed in Table 16 cover a wide variety of exact algorithms and metaheuristics, including matheuristics. Some publication propose MIPs and most exact solution approaches are based on BP algorithms. Also, matheuristics combining CG with a powerful metaheuristic component are often used and provide state-of-the-art results (cf. Prescott-Gagnon et al., 2010). Among metaheuristics, genetic algorithms and ALNS or VNS based algorithms yield the best results. LS algorithms are successfully used for TOP and TSP variants (cf. Vansteenwegen et al., 2012; Divsalar et al., 2013).

The benchmark instance sets are summarized in Table 17 for the VRP variants and in Table 18 for the TSP and TOP variants. The tables show the number of instances, the number of customers, the number of intermediate stop options (if applicable) and other papers that use the same instances. For the VRP variants, besides some early instance sets of Xu et al. (2003) and Ceselli et al. (2009), most publications use the instance set provided in Goel (2009). Only Schiffer et al. (2017a) propose different instance sets, limited to a one-day planning horizon in mid-haul logistics and accounting for the characteristics of ECVs. Instance sets for the TSP variants with up to 1002 customers are given in Vansteenwegen et al. (2012), and the most common benchmark for the TOP with hotel selection is presented in Divsalar et al. (2013).

Table 16: Solution methods for intermediate stops for break and rest periods.

Exact	
(M)I(L)P	Kok et al. (2011); Vansteenwegen et al. (2012); Divsalar et al. (2013); Li and Keskin (2014)
BP / CG	Xu et al. (2003); Ceselli et al. (2009); Prescott-Gagnon et al. (2010); Goel and Irnich (2016)
lower bound	Xu et al. (2003)
DP	Xu et al. (2003); Ceselli et al. (2009); Kok et al. (2010); Goel and Irnich (2016)
	Heuristic
TS	Prescott-Gagnon et al. (2010); Castro et al. (2013); Rancourt et al. (2013)
(A)LNS	Goel (2009); Prescott-Gagnon et al. (2010); Schiffer et al. (2017a)
(A)VNS	Divsalar et al. (2013, 2014a)
LS	Vansteenwegen et al. (2012); Divsalar et al. (2013); Schiffer et al. (2017a)
EA	Castro et al. (2013); Divsalar et al. (2014b,a); Goel and Vidal (2014)
SA	Li and Keskin (2014)
Other	Xu et al. (2003); Kok et al. (2010, 2011); Baltz et al. (2015)

Abbreviations hold as follows: (M)I(L)P - (mixed) integer (linear) program; DP - dynamic programing; BP - branch and price; CG - column generation; LB - lower bound, TS - tabu search; (A)LNS - (adaptive) large neighborhood search; (A)VNS - (adaptive) variable neighborhood search; LS - local search; EA - evolutionary algorithm; SA - Simulated Annealing.

Table 17: Instances for the VRTDSP.

Reference	Type	I	C	IF	Used within
Xu et al. (2003)	AIF	19	50-210		
Xu et al. (2003)	AIF	15	300-500		
Ceselli et al. (2009)	AIFMRD	46	1-47		
Goel (2009)	AIFTW	56	100		Kok et al. (2010); Prescott-Gagnon et al. (2010); Kok et al. (2011); Goel and Vidal (2014); Goel and Irnich (2016)
Rancourt et al. (2013)	AIFTW	1	162		
Rancourt et al. (2013)	AIFTW	56	100		
Schiffer et al. (2017a)	ADPIFTW	56	100	897	

Table 18: Instances for TSPs / TOPs with hotel selection.

Reference	Type	I	C	IF	Used within
Vansteenwegen et al. (2012)	AIFMRD	16	48–288	5	Castro et al. (2013); Baltz et al. (2015)
Vansteenwegen et al. (2012)	AIFMRD	16	10–40	1	Castro et al. (2013); Baltz et al. (2015)
Vansteenwegen et al. (2012)	AIFMRD	48	51–1002	3-10	Castro et al. (2013); Baltz et al. (2015)
Li and Keskin (2014)	AIFTW	32	16–32	4–32	
Divsalar et al. (2013)	AIFMRD	105	32–102	1-3	Divsalar et al. (2014b,a)
Divsalar et al. (2013)	AIFMRD	70	32-102	5-6	Divsalar et al. (2014b,a)
Divsalar et al. (2013)	AIFMRD	44	64–100	10-12	Divsalar et al. (2014b,a)
Divsalar et al. (2014b)	AIFMRD	176	65–130	3-15	Divsalar et al. (2014a)
Baltz et al. (2015)	AIFMRD	210	5–50	5–50	

Concluding, problems arising in the context of routing with intermediate stops for idling, namely the VRTDSP as well as TSPs and TOPs with hotel selection, remain a young and active research field which has gained interest in recent years. Methodologically, problem variants will stick to the already addressed ones (mainly AIFMRD and AIFTW) due to the application cases. However, more complex variants like the ADPIFTW resulting out of the EVRPTDS may arise when HOS regulations or other idling options are integrated into rich routing problems. Generally, specific case studies on the (known) methodologically proposed problem variants are still sparse. For the VRTDSP, it is mainly long-haul routing that has been addressed until now (except for Schiffer et al. (2017a)). Aiming at real-world cases in rich VRPs, integrating HOS regulations into mid-haul routing seems to be an interesting option. Furthermore, analyzing more specific regulations (e.g., as in Kok et al. (2010)) may inspire researchers in this field.

5 Conclusion

We have studied RPISs. An intermediate stop has been defined to be a stop en route that is not related to providing service, but is necessary to keep the vehicle operational. This definition was used to distinguish this problem class from multi-echelon problem variants. Routing problems for intermediate stops have been divided into three large application areas, namely *i*) replenishment and unloading, *ii*) refueling, and *iii*) idling for breaks and rests. A nomenclature to characterize routing problems with intermediate stops has been introduced and used to point out the decisive modeling characteristics of these problems. Furthermore, algorithmic findings have been identified for the different problem variants, and effective solution techniques have been highlighted, e.g., adding dynamic programming components to optimally locate intermediate stops on routes in metaheuristics.

This survey showed that the three application areas have known different temporal developments. While routing problems with intermediate stops for replenishment and unloading have constantly been investigated due to the relevance in municipal services and classical logistics services, routing problems with intermediate stops for refueling and idling have been ignored for a long time. Routing problems for refueling have traditionally been limited to ICEVs, but have become popular in recent years due to the increasing role of AFVs, especially ECVs, in sustainable transportation. RPISs for idling have known a peak in recent years as researchers have paid increasing attention to rich VRPs.

Besides providing an in-depth overview on routing problems with intermediate stops, this survey has identified some promising directions for future research. First, uncertainty with respect to travel times or customer patterns has not been included in existing approaches so far. Only a few recent publications include uncertain customer patterns (cf. Schiffer and Walther, 2017c) or uncertain charging behavior (cf. Sweda et al., 2017). Thus, including uncertainty into the addressed problem classes seems to be a challenging and interesting research direction. Second, the first LRP approaches that highlight the interdependencies between charging station location and vehicle routing decisions have just been published. However, the resulting improvement potential has so far been neglected in network design for intermediate stops for replenishing and unloading. Regarding this issue may reveal significant cost improvements for these application cases. A first paper in this direction has recently been published by Schiffer et al. (2017c). Third, papers dealing with real-world applications are still sparse for problems that focus on either refueling stops or idling stops for HOS regulations. Especially, regarding intermediate stops for refueling of ECVs, future work on case studies may pave the way for a market uptake of ECVs and thus, more sustainable and environmentally friendly means of transportation.

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