The Combination Truck Routing Problem: A Survey

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Abstract

The combination-vehicle attributes of vehicle routing problems are additional characteristics that aim to consider more effectively the specificities of real logistics applications. Because various combination truck situations exist, the combination truck routing problem (CTRP) is supported by well-developed literature, especially with respect to the truck and trailer routing problem (TTRP), the rollon-rolloff vehicle routing problem (RRVRP), the tractor and semitrailer routing problem (TSRP), and a variety of heuristics. This article first reviews the three primary forms of the CTRP, providing a survey of problem foundations and heuristics for the TTRP, the RRVRP and the TSRP. Next, this report takes a closer look at comparing the three forms of the CTRP. The TTRP aims to efficiently apply trailers that can attach/detach trucks easily to serve less-than-truckload shipping, and the RRVRP and the TSRP aim to attain high use rates for tractors in different full truckload shipping practices. The three forms of the CTRP share a number of common features. In particular, most of the formulations and heuristic strategies developed for specific problems share many similar characteristics. The CTRP is an extremely rich and promising operations research field. More general formulations and more general-purpose solvers are necessary to address practical combination truck routing applications efficiently and in a timely manner.

1. Introduction

The mode of constitution of the autonomous and non-autonomous parts of vehicles makes it possible to classify trucks into two main types [15]: single-unit trucks and combination trucks. A single-unit truck (e.g., \( \text{Fig. 1} \)) has fixed autonomous and non-autonomous parts, and the two parts cannot be separated. Combination trucks include...
truck tractor-semitrailer combinations (e.g., III in Figure 1) and trucks or truck tractors with semitrailers in combination with full trailers (e.g., II and IV in Figure 1).

Note: In practice, many vehicle types are used in road freight transportation. This figure lists only four basic types. A large number of other types can be built from the four basic types with different axle configurations, number of tires, number of trailers, and combination styles.

Fig. 1. The basic types of road freight vehicles (Li et al., 2012)

As one of the most studied combinatorial optimization problems, the vehicle routing problem (VRP) was first proposed in the late 1950s [11]. The VRP is concerned with the optimal design of routes to be used by a fleet of vehicles to serve a set of geographically scattered customers. The VRP is considered central to distribution management and must be routinely solved by carriers. van Duin et al. [36] stated that the VRP can be used as a principal tool for planning the operations of many types of city logistics schemes. Small-capacity vehicles are practically permitted in city logistics systems, so the VRP generally focuses on the route optimization of small-capacity vehicles.

In practice, large-capacity vehicles are employed more often than small-capacity vehicles. In the U.S., heavy-duty truck traffic increased 77% between 1990 and 2006, whereas light-duty truck traffic increased 66% in the same period [35]. Combination trucks are generally large capacity and are fit for intercity line-haul logistics. Disregarding the safety impacts of combination trucks, especially in urban or hilly conditions, combination trucks allow increased use rates for trucks or tractors. The average vehicle travel per combination truck is five times that per heavy single-unit truck or that per light-duty truck in the U.S. [12]. Although combination trucks comprise only 2% of all registered vehicles, they constitute nearly 11% of vehicle travel and account for over 27% of US transportation-based fuel consumption.

Focusing on optimizing combination truck dispatches is desirable. Some researchers think the combination truck routing problem (CTRP) is at least as difficult as the VRP, which is NP-Hard [8,32,26]. Because various types of combination trucks are employed by logistics enterprises around the world, the CTRP can have various practical backgrounds. Researchers have so far put forward three types of CTRPs: the truck and trailer routing problem (TTRP), the rollon-rolloff vehicle routing problem (RRVRP) and the tractor and semitrailer routing problem (TSRP).

The objective of the paper is twofold. First, we formally describe the three types of CTRPs and review the algorithms for the TTRP and the RRVRP. Second, we compare the current state of the art of mathematic models and solving algorithms of the CTRP and offer suggestions for future research.

2. The TTRP

As the earliest put-forward form of the CTRP, the TTRP has attracted researchers’ attention for over twenty years. Lin et al. [26] described the TTRP based on the VRP as follows. A set of customers with known demand and location is served by a fleet of homogeneous combination vehicles with known capacity. The vehicles may be a truck pulling a trailer, called a complete vehicle, or a single truck, called a pure truck. Because of some conditions, several customers can be served only by a pure truck (called truck customer, TC) and others can be reached either by a pure truck or by a complete vehicle (called vehicle customer, VC). There are three types of routes in the solution of the TTRP: i) the Pure Truck Route (PTR), which contains VCs or TCs served by a pure truck alone, ii) the pure vehicle route (PVR), which is traveled by a complete vehicle and contains only VCs without any sub-tours, and iii)
the complete vehicle route (CVR), which consists of a main tour traveled by a complete vehicle and at least one sub-tour served by a pure truck. A sub-tour starts from and returns to a customer found in the main tour. The truck detaches the trailer and parks it at the root customer of the sub-tour and returns to attach the trailer after serving the customers on the sub-tour. The main tour contains only VC customers, whereas the sub-tours contain VCs or TCs. The objective is to minimize the total cost of the route plan.

2.1. The approximative form

Semet and Taillard [34] presented some actual application related to the TTRP in the early 1990s. The problem occurred in a major chain store with 45 grocery stores, of which 9 were trailer stores and 36 were truck stores located in Switzerland. A heterogeneous fleet of vehicles consisting of 21 trucks and 7 trailers was used to serve the stores. The goal was to determine a route schedule using the heterogeneous fleet that minimized the transportation costs. The time windows of the stores and vehicle-dependent costs were also taken into account. How this problem differs from the basic TTRP is that the vehicle customers (trailer stores) cannot be served in a sub-tour. Semet [33] modeled the partial accessibility constrained vehicle routing problem (PACVRP), which was an extension of the VRP and took the partial accessibility constraint into account. Two categories of customers were defined: trailer customers and truck customers. The PACVRP is very similar to the basic TTRP. Gerdessen [17] proposed another problem related to the TTRP, called the vehicle routing problem with trailers (VRPT). In the VRPT, the use of combination vehicles may cause trouble when serving customers with constraints. Time and trouble could be saved if these customers were served by a truck alone. The trailer needed to be parked at some points, and the truck delivered the products to the customers along a certain route.

2.2. The basic TTRP

Chao [8] described a form of the TTRP, which was followed by the majority of subsequent research work. Therefore, we suggest the basic TTRP as follows. Consider an undirected complete graph \( G = (V, A) \) where \( V = \{0, 1, 2, \cdots, n\} \) is the vertex set and \( A = \{(i, j) \mid i, j \in V, i \neq j\} \) is the set of edges. The vertices denote the customers, except the vertex 0, which corresponds to the depot. Each customer \( i \in V \setminus \{0\} \) has a positive demand \( q_i \), and there is a symmetric, nonnegative cost \( c_{ij} \) associated with each arc \( (i, j) \in A \), where \( c_{ij} \) is the Euclidean distance between vertex \( i \) and \( j \). Let \( m_k \) and \( m_r \) \((m_k \geq m_r)\) represent the number of the trucks with capacity \( Q_k \) and trailers with capacity \( Q_r \), respectively. In the solution of the basic TTRP, there will be \( m_k \) pure and complete vehicle routes and \( m_r \) pure truck routes. The total demand of the customers cannot exceed the total capacity of the complete vehicle \( (i.e., Q_k + Q_r) \) for each PVR and CVR and the capacity of the truck \( (i.e., Q_r) \) for each PTR. In particular, the total demand of each sub-tour cannot exceed \( Q_k \). Besides, Villegas et al. [39] proposed a set-partitioning formulation of the basic TTRP.

2.3. The TTRP extensions

Researchers extended the basic TTRP to various forms to meet certain practical requirements. The typical extensions of the TTRP include the following.

- The relaxed TTRP (RTTRP). Lin et al. [27] noted that in the basic TTRP, there were no fixed costs associated with the vehicle, although there were limitations on the number of available trucks and trailers. It was possible to construct better vehicle routes by utilizing more vehicles or allowing vehicles to take on multiple trips. Further, if the reduction in costs resulting from such a relaxation is significant, it may be worthwhile to acquire or lease extra vehicles, provided that the acquisition/lease costs can be justified. Therefore, the fleet size constraint in the basic TTRP was relaxed. The resulting RTTRP can also be used to determine a better fleet mix.

- The TTRP with time windows (TTRPTW). The TTRPTW was first presented by Lin et al. [28] and followed by other researchers [4]. The TTRPTW can be regarded as a variant of the VRPTW. In the TTRPTW, all customers should be served in their specific time windows. The number of trucks and trailers used in the routes was not determined a priori.
The extended TTRP (ETTRP). The basic TTRP assumes that a truck is allowed to park its pulling trailer at any appropriate VC before proceeding to serve the customers along a sub-tour. However, this may not be acceptable for some reasons. Zitz [42] defined the ETTRP to separate parking places from customers. In the ETTRP, the VCs were no longer considered feasible parking places. A parking place may be used any number of times within the same or different routes. In addition, time windows and load constraints were also considered by the ETTRP.

The generalized TTRP (GTTRP). Drexl [16] presented the GTTRP and a unified model for the VRPs with trailers and a fixed truck-trailer assignment. The GTTRP gave a set of transshipment locations used for parking and/or load transfer. Visiting a transshipment location incurred only the distance-dependent cost for the resulting detour. To extend the GTTRP, Drexl [15] presented the VRP with trailers and transshipment (VRPTT), which constituted an archetypal representative of the class of VRPs with multiple synchronization constraints (VRPMSs). In the VRPTT, there was no longer a fixed assignment for a truck to a trailer; that is, each trailer may be pulled by any truck. Drexl [15] also described several applications of the VRPTT.

The single truck and trailer routing problem with satellite depots (STTRPSD). Villegas et al. [37] presented the STTRPSD, where a single vehicle composed of a truck with a detachable trailer served the demand of a set of customers reachable only by the truck. A set of parking locations, called trailer points or satellites, was available. In the feasible solution of the STTRPSD, a subset of trailer points were chosen to be open, and each customer was assigned to one trailer point.

2.4. Computational experiments

We classify the publicly available test instances for the TTRP as two types: instances modified and derived from the benchmark instances for the VRP and instances abstracted from logistics enterprise practices. The TTRP models presented above can be solved by heuristics to attain suboptimal solutions of a priori unknown quality.

- **Tabu search.** Semet and Taillard [34] used a standard tabu search method to solve a real-life TTRP instance. The problem dealt with 70 to 90 orders. A heterogeneous fleet of vehicles consisting of 21 trucks and 7 trailers was available. Chao [8] developed a 2-phase approach consisting of a solution construction method and a tabu search improvement heuristic coupled with the deviation concept found in deterministic annealing. Seven benchmark instances of VRPs were selected from Christofides et al. [9] and were converted to 21 TTRP instances. The computational tests showed that the proposed approach can consistently, effectively and efficiently solve the TTRP. Scheuerer (2006) proposed two new construction heuristics and a tabu search heuristic for the TTRP. Details on sensitivity analyses for the tabu search parameters were also presented. The proposed approach can obtain better solutions for the 21 test instances designed by Chao [8].

- **Simulated annealing.** Lin et al. (2009) applied a simulated annealing heuristic to solve the TTRP. 17 best solutions to 21 TTRP benchmark instances provided by Chao [8], including 11 new best solution and 6 previously reported best solutions, were found. Moreover, the computational time required by the proposed simulated annealing heuristic was less than those of the reported approaches. The simulated annealing was later applied to solve the RTTRP [27] and the TTRPTW [27].

- **Neighborhood search.** To solve the TTRP, Villegas et al. (2011) used a route-first, cluster-second procedure embedded within a hybrid meta heuristic based on a greedy randomized adaptive search procedure (GRASP), a variable neighborhood search (VNS) and a path relinking (PR). When solving the 21 benchmark instances provided by Chao [8], the proposed approach obtained average gaps to best-known solutions of less than 1%. Villegas et al. [39] proposed an effective two-phase matheuristic that used the routes of the local optima of a hybrid GRASP×ILS as columns in a set partitioning formulation of the TTRP. The performance of the proposed method was evaluated in two sets of instances. The first testbed was introduced by Chao [8], and the second testbed introduced by Lin et al. [27].
3. The RRVRP

As shown in the experimental results of Pradenas et al. [31], the types of vehicles and the use rates of vehicles are important factors affecting fuel consumption from vehicle routing. When truck tractor-semitrailer combinations are used for freight transportation, the tractor has a high use rate. The tractor cannot load goods and is only used for pulling trailers. Because the time needed to attach/detach a semitrailer to a tractor at locations is usually considerably less than the time needed to load/unload all cargo in a semitrailer, the waiting time of tractors is noticeably reduced. A typical form of the tractor-semitrailer combination routing problems is the RRVRP.

3.1. The basic RRVRP

Waste collection is the main practical background of the RRVRP. Golden et al. [18] introduced three types of waste collection problems: residential, commercial, and industrial. The customers require large-container level services, and the resulting problem is abstracted as the RRVRP.

De Meulemeester et al. [13] solved a complex routing problem associated with the collection and delivery of skips. All collections and deliveries were made by a fleet of vehicles based at a depot. A vehicle can carry only one skip at a time. Two types of customers were considered: domestic and industrial. All domestic customers used the same dump located next to the depot; industrial customers used one of several dumps located far from the depot.

Bodin et al. [5] presented the basic RRVRP. In a graph \( G = (V, A) \), \( V \) is the vertex set consisting of the depot located at vertex \( v_0 \), the disposal facility located at vertex \( v_d \), which is also taken as an unlimited inventory of empty trailers, and the \( n \) customer locations \( \{v_1, v_2, \ldots, v_n\} \), of which each one is visited by a single trip. Each arc \((i, j)\) of the arc set \( A \) is associated with a travel time \( \tau_{ij} \). Four types of trips \( T_i (i=1,2,3,4) \) are defined in the basic RRVRP: (i) The tractor attaches a full trailer at a customer location, goes to the disposal facility, waits for the trailer to be emptied, and then takes the empty trailer to the same customer location where the trailer is detached from the tractor. (ii) The tractor attaches an empty trailer at the disposal facility, goes to a customer location where the empty trailer is detached from the tractor, and then the tractor takes a full trailer back to the disposal facility. (iii) The tractor attaches an empty trailer at the disposal facility and then takes it to a customer location where the empty trailer is detached from the tractor. (iv) The tractor attaches a full trailer at a customer location and takes it back to the disposal facility. Bodin et al. [5] took the basic RRVRP as a combination of the asymmetric vehicle routing problem (AVRP) and the bin packing problem (BPP).

3.2. The RRVRP extensions

Researchers have extended the basic RRVRP to a number of forms. For example, Baldacci et al. [1] proposed the multiple disposal facilities and multiple inventory locations RRVRP (M-RRVRP). Five types of trips are considered. The M-RRVRP is modeled as a time constrained VRP on a multiGraph (TVRP-MG). Time window is another extension factor. Wy et al. [41] considered the time window and presented the RRVRP with time windows (RRVRPTW). In the RRVRPTW, there are multiple disposal facilities and multiple inventory locations. The objective of the RRVRPTW is to minimize the number of required tractors first and the total time of all routes second. Hauge et al. [20] addressed another type of the RRVRP in which four types of trips are considered. Multiple depots, disposal facilities and container types are also considered. The goal is to minimize the total time to complete all trips.

3.3. Computational experiments

Bodin et al. [5] tested four heuristics on four classes of benchmark instances ranging from 50 to 199 trips. The four heuristics were the decomposition algorithm (DA), the partial enumeration method (PEM), the trip insertion/trip improvement algorithm (TI²), and simulated annealing (SA). Derigs et al. [14] used an approach combining standard local search and large neighborhood search moves under two parameter-free/-poor metaheuristic controls. Twenty benchmark instances provided by Bodin et al. [5] were used to test the approach. Wy
and Kim [41] proposed a hybrid metaheuristic approach that consists of a large neighborhood search and various improvement methods to solve the RRVRP. New best-known solutions are found for 17 instances out of 20 benchmark instances provided by Bodin et al. [5].

Baldacci et al. [1] developed an exact method for the M-RRVRP. The method is based on a bounding procedure combining three lower bounds derived from different relaxations of the formulation of the M-RRVRP. The computational results show that the method is effective in deriving an optimal or near optimal solution to the M-RRVRP in a reasonable computing time.

Wy et al. [41] proposed a large neighborhood search based iterative heuristic approach consisting of several algorithms for the RRVRPTW. 34 benchmark instances were developed, in which 14 were derived from a real waste collection company in the US, and 20 were artificially generated. The proposed approach generates much better solutions in terms of the number of tractors required and the total route time for the benchmark data than the current company practices.

4. The TSRP

The main contribution of the TSRP to the literature is that it extends the existing studies on the RRVRP to a problem with a tractor and semitrailer combination considered in an intercity line-haul network with many-to-many demand. The research on the TSRP takes China’s increasingly popular tractor and semitrailer transportation as the practical background [24].

Compared with most VRP studies employing trucks to serve the delivery and/or pickup of city logistics, the TSRP utilizes tractor-semitrailer combinations to serve the intercity logistics. Unlike other related problems, such as the VRP or the traveling salesman problem (TSP), which are considered one-to-many problems (Barcos et al., 2010), the type of problem considered in the intercity line-haul tier resembles a many-to-many problem. The TSRP was proposed in a loaded-semitrailer flow network [25]. A set of full truckloads (i.e., O-D pairs with associated loaded-semitrailer exchange demand) that need to be transported is given. There are two types of terminals in the network: one central depot and a number of satellite depots. At the beginning, all tractors are assigned to the central depot, where they must return to after each route. Each terminal may have some loaded-semitrailers waiting to be sent to other depots. Each tractor can leave from and return to the depot once or more. A tractor can pull one loaded semitrailer and can run alone to visit depots. Typically, satellite depots must send more than one loaded semitrailer and must be visited more than once. The objective of the TSRP is to determine the number of tractors and the route of each tractor to minimize CO2 emissions per ton-kilometer. The TSRP takes CO2 emissions per ton-kilometer as the objective to observe the effects of tractor and semitrailer routing on the mitigation of CO2 emissions for intercity line-haul road freight transportation. The solution method is tested on some small-scale instances generated randomly and some realistic instances. As the experimental results of Li et al. (2013b), the effects of the tractor and semitrailer routing on the mitigation of carbon dioxide emissions are obvious. In addition, regardless of the instance, the objective value fluctuates within a relatively small range because the TSRP takes the efficiency index (i.e., CO2 emissions per ton-kilometer) as the objective.

5. Comparison of various CTRPs

5.1. The difference of various CTRPs

The road transportation types can be divided as long-haul transports and distribution transports by transporting distances. The vehicle types used by road freight transportation and the transportation types classified by transporting distances theoretically provide four situations for the background of the VRP study. i) trucks used for long-haul transports, ii) trucks used for distribution transports, iii) combination vehicles used for long-haul transports, and iv) combination vehicles used for distribution transports.

Most distribution transports operating around terminals have short distances. Despite the relative short distances compared to the long haul, distribution transports can be responsible for up to 40% of the total transportation cost [6]. A great deal of the VRP study concentrates on distribution transports. Furthermore, additional operational requirements and restrictions on road vehicles may be imposed on the VRP.
Table 1. A classification of the VRP and various extensions

<table>
<thead>
<tr>
<th>Distance</th>
<th>Truck type</th>
<th>Single-unit Truck</th>
<th>Combination truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution / delivery</td>
<td>VRP</td>
<td>——</td>
<td>TTRP, RRVRP</td>
</tr>
<tr>
<td>Line-haul transport</td>
<td>——</td>
<td>——</td>
<td>TSRP</td>
</tr>
</tbody>
</table>

Table 1 classifies the VRPs and various CTRPs by vehicle types and transport distances. The RRVRP in the waste collection field is a relatively new type of routing problem. The TSRP extends the vehicle of the RRVRP to the application of the line-haul network with many-to-many demand. The following are obvious differences among the VRPs and the CTRPs.

First, different tiers of logistics systems decide the graphs and the transport demand in routing problem models. For example, in two-tiered city logistics systems, the first tier involves vehicles delivering freight from the city distribution centers (CDCs) to satellites facilities, and the second tier involves vehicles performing the satellite-to-customer delivery routes. A CDC is not the origin of freight. There is an intercity line-haul tier that involves large-capacity vehicles transporting freight among CDCs of various cities. In the literature, the TTRP and the RRVRP are one-to-many problems, whereas the TSRP is a many-to-many problem. In addition, large-capacity vehicles accounting for the bulk of transportation between CDCs allows economies of scale, thereby lowering intercity shipping costs. At the intermediary facilities of city logistics systems such as CDCs, large-capacity vehicles are transferred to small-capacity vehicles.

Second, the road freight industry basically has two types of service segments: full truckload (TL) shipping and less-than-truckload (LTL) shipping. TL is more suitable for terminals with large shipment sizes that require individual tailored services; LTL is more appropriate for clients who have to share the carrier’s transportation resources with other customers [7]. The VRP and the TTRP research concentrates on the optimization of delivery or/and pickup of LTL service while semitrailers are fit for TL in the RRVRP and the TSRP. Therefore, the units of measurement for the transport demand of different routing problems are possibly different. The VRP and the TTRP take cargo weight as the unit of measurement, whereas the RRVRP and the TSRP take a semitrailer as the measure unit.

5.2. A generalized form of the CTRPs

Consider a directed graph \( G = (V, A) \), where \( V = \{0,1,2,\ldots,n\} \) is the set of vertices and \( A = \{(i,j) \mid i, j \in V\} \) is the set of arcs. Vertex 0 (\( V_0 \)) represents the central depot (or the regional terminal) and the remaining vertices (\( V_i \)) in \( V \) (i.e. \( V \setminus \{0\} \)) correspond to satellite depots (or end-of-line customer terminals). Let \( PA_0 \) be the vertex-arc incidence matrix of the complete network connecting the \( n+1 \) terminals. The incidence matrix has \( n+1 \) columns and \( P_{n+1}^{2} \) rows. \( PA_0 \) is divided into two equal-dimension matrixes \( PA_0 \) and \( PA_2 \). There are only values of “1” and “0” in \( PA_2 \) and there are only values of “-1” and “0” in \( PA_2 \). Thus, \( PA_0 = PA_1 + PA_2 \).

- **Fleet of vehicles**
  A vehicle is made up of autonomous and non-autonomous parts. The number of autonomous parts departing from vertices \( V_i \) (\( i = 0,1,2,\ldots,n \)) and passing by the \( P_{n+1}^{2} \) arcs is denoted by \( T_i = (t_{i,1},t_{i,2},\ldots,t_{i,P_{n+1}^{2}}) \). All autonomous parts departing from all vertices are \( T = (T_0,T_1,T_2,\ldots,T_n) \). The quantity of loaded non-autonomous parts departing from vertices \( V_i \) (\( i = 0,1,2,\ldots,n \)) and passing by the \( P_{n+1}^{2} \) arcs is denoted by \( S_i = (s_{i,1},s_{i,2},\ldots,s_{i,P_{n+1}^{2}}) \). All loaded non-autonomous parts departing from all vertices are \( S = (S_0,S_1,S_2,\ldots,S_n) \). Suppose the ratio between the autonomous part and the non-autonomous part of an on-road running vehicle is \( 1: k \).

- **Freight flows**
  There are three types of freight flows over the network given by \( G: d \) is the vector of scalars \( d_{i,0} \) that gives the freight flow from \( V_0 \) to \( V_i \), with \( d = (d_{0,1},d_{0,2},\ldots,d_{0,n}) \). \( p \) is the vector of scalars \( p_{i,0} \) that gives the freight flow
from \( v_i \) to \( v_0 \), with \( p = (p_{10}, p_{20}, \cdots, p_{n0}) \), and \( a \) is the matrix of scalars \( a_{ij} \) that gives the freight flow from \( v_i \) to \( v_j \) (\( i, j = 1, 2, \cdots, n \)), with

\[
\begin{bmatrix}
0 & a_{12} & a_{13} & \cdots & a_{1n} \\
0 & a_{21} & a_{23} & \cdots & a_{2n} \\
a_{31} & a_{32} & 0 & \cdots & a_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{n(n-1)} & 0
\end{bmatrix}
\]

- Variable costs

The variable costs of autonomous parts departing from vertices \( v_i \) and passing by the \( P_{n+1}^{2i} \) arcs are denoted by \( TC_i = (tc_{i,1}, tc_{i,2}, \cdots, tc_{i,P_{n+1}^{2i}}) \) (\( tc_{i,j} = 0 \)). The total variable costs of all autonomous parts departing from all vertices are \( TC = (TC_1, TC_2, \cdots, TC_n) \). The variable costs of loaded non-autonomous parts departing from vertices \( v_i \) and passing by the \( P_{n+1}^{2i} \) arcs are denoted by \( SC_i = (sc_{i,1}, sc_{i,2}, \cdots, sc_{i,P_{n+1}^{2i}}) \) (\( sc_{i,j} = 0 \)). The total variable costs of all loaded non-autonomous parts departing from all vertices are \( SC = (SC_0, SC_1, SC_2, \cdots, SC_n) \).

- The model

The objective of the model is to minimize the total variable costs. The mathematical programming formulation is presented as follows:

\[
\text{Min } TC' \cdot T + SC' \cdot S
\]

The key constraints include the following:

i) The constraints that guarantee that routes are connective and closed.

ii) The constraint that guarantees that each autonomous part of the on-road vehicle can haul at most \( k \) non-autonomous parts. That is, \( k \cdot T \geq S \).

iii) The constraints that guarantee the degree of balance of each customer terminal under the condition of all autonomous parts held by the regional terminal. That is, \( PA_T \cdot T = 0 \).

iv) Freight demand constraints: the satisfaction of freight flow demands from the regional terminal to customer terminals, i.e., \( PA_S \cdot S \geq d \); the satisfaction of freight flow demands from customer terminals to the regional terminal, i.e., \( PA_S \cdot S \geq p \); and the satisfaction of freight flow demands between customer terminals.

The above model is a general form of the VRPs and the CTRPs. If \( k = 1 \) and the autonomous and non-autonomous parts of a vehicle cannot be separated freely (i.e., \( T \) and \( S \) are the same, and \( TC \) and \( SC \) are the same), the model becomes the VRPs with single-unit trucks as the transporting tools. If \( k > 1 \) and the autonomous and non-autonomous parts of a vehicle can be separated and combined freely, the model becomes the CTRPs with combination vehicles as the transporting tools. When \( p = 0 \) and \( a = 0 \), the model describes the TTRP. When \( p = 0 \) and \( d = 0 \), the model describes the RRVRP. When all constraints are considered, the model describes the TSRP.

- The solution and application

Much literature [2,22] has reviewed the solution methodology for VRPs. Commercial IP solver software may fail to provide a benchmark. In such a case, a suitable lower bound is essential to evaluate the quality of the heuristic algorithm solutions. If the number of variables and constraints in a derivative model is significantly less than those of the original model, the derivative model is expected to be solved in a much shorter time. This derivative model is solved to find lower bounds on the objective values of the solutions to the original model [19]. As is mentioned, the above model is a general form of the VRPs and the CTRPs. Once the formulations confirmed, the model and its solving method is expected to serve different forms of vehicle routing. The generalized model and solution method help solving the problems how to efficiently route vehicles operating at different levels which is known in the literature as the Two-Echelon Vehicle Routing Problem (2E-VRP) [21], the generalized vehicle routing problem (GVRP) [30] or the single-sourcing two-echelon capacitated location-routing problem (2E-CLRP) [10].

6. Conclusions

Vehicle types and transport distances can be used to classify the various forms of the CTRP and the VRP. Compared to the VRP, the TTRP aims to efficiently apply trailers that can attach/detach trucks easily. The RRVRP
and the TSRP aim to attain high use rates for tractors in different practice backgrounds. When considering transport demand between nodes on graphs, the TTRP and the RRVRP are one-to-many problems, whereas the TSRP is a many-to-many problem. The research on the TTRP concentrates on the optimization of delivery and/or pickup of LTL service, whereas that of the RRVRP and the TSRP concentrates on the optimization of the line-haul of TL service.

In the area of model formulations and exact algorithms, it is apparent that the CTRP is considerably more difficult to describe and solve than the VRP. The VRP has several widely used formulations (e.g., vehicle flow formulations, commodity flow formulation, set partitioning formulation), whereas the CTRP has few formulations (e.g., set partitioning formulation). The operations research community has just about broken the 100 barrier, and it is difficult at this stage to predict how much further we can go [22]). Although some test instances of the CTRP include 50, 75, 100, 150 or 199 customers, there is no exact algorithm so far to solve such instances.

The CTRP has been a major source of motivation for the growth we have witnessed in the fields of metaheuristics. For practical purposes, the TTRP, the RRVRP and the TSRP can be solved well for realistic size instances. As this survey illustrates, a number of metaheuristic families, particularly tabu search, neighborhood search, and simulated annealing algorithms, are widely acknowledged for their performance on a variety of the CTRP. The survey also underlines that, although few general and efficient metaheuristics were proposed in the literature for the TTRP and the RRVRP, the CTRP naturally shares many common features. In particular, most of the formulations and heuristic strategies developed for specific problems share many similar constraints.

The CTRP is a very rich and promising field of research, particularly given the trend toward problem settings including a continuously increasing number of attributes. Therefore, more general formulations and more general-purpose solvers, capable of handling a wide range of CTRPs, are necessary to efficiently address practical routing applications in a timely manner. Generically solving a wide range of CTRPs requires a better understanding of the problem foundations and the methods. This survey may represent a step toward reaching these goals.

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References


