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Research Article

The Effects of the Tractor and Semitrailer Routing Problem on Mitigation of Carbon Dioxide Emissions

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The incorporation of CO_2 emissions minimization in the vehicle routing problem (VRP) is of critical importance to enterprise practice. Focusing on the tractor and semitrailer routing problem with full truckloads between any two terminals of the network, this paper proposes a mathematical programming model with the objective of minimizing CO_2 emissions per ton-kilometer. A simulated annealing (SA) algorithm is given to solve practical-scale problems. To evaluate the performance of the proposed algorithm, a lower bound is developed. Computational experiments on various problems generated randomly and a realistic instance are conducted. The results show that the proposed methods are effective and the algorithm can provide reasonable solutions within an acceptable computational time.

1. Introduction and Problem Description

Along with the growth of the demand for goods, transportation volume is increasing rapidly. For door-to-door transportation, the most widely used mode is road transportation. However, road transportation has some negative impact on the environment because of the land use, energy resource consumption, and so forth. Road transportation accounts for almost 80% of total energy demands from transportation [1]. Fossil fuels are the main energy sources of transportation and CO_2 is emitted during the combustion of fossil fuels. As a dominant mode of freight movement, road transportation accounts for the largest share of the freight-related emissions [2]. The percentages of road freight transportation CO_2 emissions compared to the entire transportation sector from 1985 to 2007 in China were between 29% and 34% [3]. More and more tons of CO_2 are released into the environment annually and the road freight transportation CO_2 emissions are likely to keep growth. Recent studies on freight transportation have focused not only on cost minimization or profit maximization for a freight company but also on carbon reduction to enhance the corporate social responsibility for the company [4].

The fuel consumption is the most expensive variable cost of the transportation process to road freight transportation enterprises [5]. The efficient use of trucks and road networks becomes more and more important. Compared with costly network infrastructure modifications, optimized routing strategies have been proven to be more efficient in enhancing network capacity [6]. Optimized vehicle routing can reduce the number of trucks and utilize the network better by reducing vehicle movements. The optimization problem has been extensively studied in the literature, known as the vehicle routing problem (VRP). The VRP and its various extensions have long been one of the most studied combinatorial optimization problems due to the problem's complexity and extensive applications [7, 8].

The incorporation of the minimization of energy and CO_2 emissions in the VRP is a relatively recent topic addressed in the research work. VRP-related research that aims to minimize total fuel consumption is rather rare [9]. Kuo [9] proposed a model for calculating total fuel consumption for the time-dependent VRP. A SA algorithm was proposed. The experimental results showed that there may be a trade-off between fuel consumption, transportation time, and transportation distances. Pradenas et al. [10] presented a mathematical model for vehicle routing with time windows and backhauling. A Scatter Search (SS) metaheuristic that minimized the emission of greenhouse gases for a homogeneous vehicle fleet was designed and implemented. The experimental results showed that the environmental impacts of the vehicle routing are related to the vehicle use rate, the loads that are transported among customers, and the distances between customers.

In general, various types of vehicles are used by enterprises. Through the constitution mode of the autonomous part and the nonautonomous part [11], vehicles can be classified into two main types: trucks and combination vehicles. A truck, that is, a single-unit truck, has its fixed autonomous and nonautonomous parts and the two parts cannot be separated. Within the class of combination vehicles are truck tractor-semitrailer combinations and trucks or truck tractors with semitrailers in combination with full trailers. In some extensions of the VRP, the combination vehicles, especially the use of trailers (a commonly neglected feature in the VRP), are considered. We study a variant of the combination-vehicle routing problem where tractor-semitrailer combinations are utilized. We call this variant of the VRP as the tractor and semitrailer routing problem (TSRP). As concern over global warming has grown, reducing CO_2 emissions is becoming important for transportation. Minimizing fuel consumption will be increasingly influential in the VRP. Differing from other literature, we aim to minimize fuel consumption of the TSRP through considering the vehicle type and its use rate.

The TSRP in the paper has the following characteristics.

(1) A tractor of the tractor with semitrailer combination can pull independent semitrailers. The tractor cannot load goods and it is only used for pulling semitrailers. The time to attach/detach a semitrailer to a tractor at a location is usually considerably less than the time to load/unload all cargoes in a semitrailer, so the tractor in the TSRP has a high use rate.

(2) The transportation service provider serves the customer orders from a number of depots. Shipments occur between depots and the pickup/delivery locations of an order, and between depots. Either full truckload (TL) or less than truckload (LTL) shipments may exist. Trucks considered in the VRP are fit for LTL shipments. In the TSRP, semitrailers are fit for TL.

(3) The tractor and semitrailer transportation is promoted to be more energy-efficient than single-unit trucks transportation [12]. As mentioned by Ierland et al. [13], the CO_2 emission factor, which can be defined as CO_2 emissions per ton-kilometer (unit: g CO_2/t-km), is a typical index to describe the CO_2 emission effects of the road freight transportation.

(4) One of the important applications of the TSRP is the concept of multilevel freight distribution systems (e.g., city logistics and multimodal freight transportation systems), in which freight arrives at a central depot and is transported further to satellite facilities by larger vehicles, and the freight is then brought to the final customers by smaller vehicles. The problem of how to efficiently route vehicles operating at both levels is known in the literature as the Two-Echelon Vehicle Routing Problem (2E-VRP) [14], the generalized vehicle routing problem (GVRP) [15], or the single-sourcing two-echelon capacitated location-routing problem (2E-CLRP) [16]. The tractor and semitrailer combination has high average loads and a high use rate of tractors, which makes it feasible to be used in the level where shipments are large or TL.

We propose the TSRP on a loaded-semitrailer flow network. There are two types of terminals on the network: one central depot and a number of satellite facilities. At the beginning, all tractors locate in the central depot, while the satellite facilities have loaded-semitrailers waiting for sending. All tractors or vehicles (a vehicle is one tractor pulling one semitrailer) originate and terminate at the central depot. A homogeneous fleet composed of tractors and semitrailers serves the flow demand among terminals. A tractor can pull one loaded-semitrailer and can also run alone. The loaded-semitrailers are assumed TL. The objective of the TSRP is to determine the number of tractors and the route of each tractor so as to minimize CO_2 emissions per ton-kilometer.

There are some features that distinguish the TSRP from existing research on routing problems. Firstly, we extend the application background of tractor and semitrailer combinations to the TL transportation course of multilevel freight distribution systems. The application of the TSRP is different from tractor and semitrailer combination applications in the literature, which is called the roll-on roll-off vehicle routing problem (RRVRP). Secondly, the TSRP takes a composite index, that is, CO_2 emissions per ton-kilometer, as the objective. It is different from most of the VRPs which take single index (e.g., total distance, total cost, etc.) as the objective. In practice, statistical data on CO_2 emissions per ton-kilometer can be used to calibrate the experimental results of the TSRP. Thirdly, the nodes of the TSRP may send more than one loaded-semitrailer and the nodes and linked arcs must be visited more than once. A node may appear more than once in the same route of the solution.

Our interest in the TSRP arises from real-life regional-level truck operations in China and the TL transporting of multilevel freight distribution systems. Our aim is to develop a solving method for the TSRP and to demonstrate the effect of CO_2 emission mitigation. The paper is organized as follows. The next section introduces the relevant literature. A mathematical model and a lower bound for the TSRP are developed in Section 3. Section 4 proposes the heuristic algorithm for solving the problem. Computational experiments are described in Section 5. Finally, conclusions and future work are given in Section 6.

2. Literature Review

In this section we turn to an overview of contributions to the combination-vehicle routing problem the TSRP addresses.

Research on the VRP to date has considered especially trucks, truck and full trailer combinations. The truck and trailer routing problem (TTRP) has been brought forward for decades. In the TTRP, a heterogeneous fleet composed of trucks and truck and full trailer combinations serves a set of customers. Each customer has a certain demand, and the capacities of the trucks and trailers are determinate. Some customers must be served only by a truck, while other customers can be served either by a truck or by a combination vehicle. The objective of the TTRP is to find a set of routes with minimum total distance or cost so that each customer is visited in a route. Chao [17] distinguished three different types of routes in a TTRP solution: a pure truck route (PTR) where a truck serves all customers without using a trailer, a pure vehicle route (PVR) where all customers are served by a truck with a coupled trailer, and a complete vehicle route (CVR) where at least once the trailer is uncoupled from the truck at a vehicle customer and the truck continues serving a subset of customers on a truck subroute.

Semet and Taillard [18] and Gerdessen [19] studied the TTRP in the 1990s. Semet and Taillard [18] and Caramia and Guerriero [20] gave some real-world TTRP applications. Gerdessen [19] extended the VRP to the vehicle routing problem with trailers and investigated the optimal deployment of a fleet of truck-trailer combinations. Scheuerer [21] proposed construction heuristics along with a Tabu search algorithm for the TTRP. Tan et al. [22] proposed a hybrid multiobjective evolutionary algorithm to solve the TTRP. Lin et al. [23] proposed a simulated annealing (SA) heuristic for the TTRP. Villegas et al. [24] solved the TTRP by using a hybrid metaheuristic. On the extensions of the TTRP, Villegas et al. [25] proposed two metaheuristics to solve the single truck and trailer routing problem with satellite depots (STTRPSD). Considering the number of available trucks and trailers being limited in the TTRP, Lin et al. [26] relaxed the fleet size constraint and developed a SA heuristic for solving the relaxed truck and trailer routing problem (RTTRP). Lin et al. [27] proposed a SA heuristic for solving the truck and trailer routing problem with time windows (TTRPTW). Recently, Derigs et al. [28] combined local search and large neighborhood search metaheuristic to solve the TTRP with/without load transfer and the TTRP with/without time windows. Computational tests on benchmark instances showed that the approach was at least competitive to state-of-the-art approaches for the TTRP without time windows.

In the TTRP, each trailer can be pulled by a unique associated truck, and only this truck is permitted to transfer the load into the trailer. The amount of trucks is generally more than that of trailers. Drexl [11] described the VRP with trailers and transshipments (VRPTT) in which there is no fixed truck-trailer assignment. The TTRP is evidently a special case of the VRPTT. Besides, Pureza et al. [29] addressed the VRP with time windows and multiple delivery men (VRPTWMD) that allows a number of delivery men to be assigned to each route. Two solution approaches based on Tabu search and ant colony optimization were proposed. The impact of the use of extra delivery men in route planning was assessed by means of computational experiments. If regarding delivery men as trucks, the VRPTWMD becomes the TTRP when there is only one deliveryman.

There are several variants of the VRP which consider tractor and semitrailer combinations. These variants include the RRVRP and others. In the literature, the RRVRP arises when tractors move large trailers between locations generating a high volume of waste like construction sites and disposal facilities. In the basic RRVRP, there is a single depot where all tractors are located at the beginning. There is a single disposal facility where full trailers are dumped and empty trailers can be put on or pulled from inventory. At the end of the day, all tractors return to the depot while trailers may remain at customer locations or the disposal facility. The problem is to assign trips to tractors and to find routes for the tractors that do not exceed a given maximal duration and that minimize the nonproductive deadhead time of tractors between trips as well as the number of tractors used.

Bodin et al. [30] studied the RRVRP with a depot and a disposal site and classified customer demands into four trip types. They defined the RRVRP as a combination of an asymmetric vehicle routing problem with a bin packing problem. Heuristic methods were proposed to solve some benchmark problems on the RRVRP. Derigs et al. [31] solved the RRVRP by combining local search and large neighborhood search controlled by two relatively simple and parameter-free/-poor metaheuristic control procedures. Wy et al. [32] introduced the RRVRP with time windows (RRVRPTW). The objective of the RRVRPTW is to minimize the number of required tractors and their total route time. A LNS based iterative heuristic approach consisting of a construction algorithm and several improvement algorithms was proposed. Baldacci et al. [33] modeled the multiple disposal facilities and multiple inventory locations RRVRP (M-RRVRP) as a time constrained vehicle routing problem on a multigraph.

There are other variants concerning the tractor and semitrailer combination routing problem. Hall and Sabnani [34] studied routes that consisted of two or more segments and two or more stops in the route for a tractor. Control rules based on predicted route productivity were developed to determine when to release a tractor. Francis et al. [35] solved the multiresource routing problem (MRRP) with flexible tasks. Two resources (tractors and trailers) performed tasks to transport loaded and empty equipment. Cheng et al. [36] proposed a model for a steel plant to find the tractor and semitrailer running routes for the purpose of minimizing transport distance. Derigs et al. [37] presented two approaches to solve the vehicle routing problem with multiple uses of tractors and trailers. Li et al. [38] studied the tractor and semitrailer routing problem on a unit-flow network, and a heuristic algorithm was used to decide the number of tractors and the route of each tractor.

In the literature, combination-vehicle routing problem is becoming hot in recent years. The background of the TTRP applications is similar to that of the VRP, that is, city logistics or other delivery process. In fact, an intercity line-haul tier is necessary to perfect city logistics or other delivery systems. Bulk transportation of large volumes of freight between cities allows economies of scale to be achieved by using large-capacity vehicles. Although the use of tractor and semitrailer combinations is considered by the RRVRP in the literature, the RRVRP applications are mainly limited in waste collection business. Because of high use rate of tractors, tractor and semitrailer combinations are promoted to be more energy-efficient than single-unit trucks. There is another variant of the RRVRP when the application background becomes intercity line-haul transportation. Among all the work we have reviewed in literature, little work has been done on the TSRP we have described earlier. The problem considered in the present study involves incorporating CO_2 emissions minimization in the TSRP. In addition, the transportation enterprise can reject customer order either because serving the order is impossible or because the cost of serving the order is too high.

3. Model Formulation

The underlying assumptions of the TSRP model are (i) all loaded-semitrailer flow demands are known in advance. The problem is static. Empty semitrailer exchanges are ignored. (ii) Loaded-semitrailer flow demands can originate between any two terminals. At the central depot, the number of incoming semitrailers is equal to the number of outgoing semitrailers; that is, the central depot has balanced flows. (iii) Some loaded-semitrailer flow demands may be rejected. The transportation service level is based on the percentage of flow demands that are satisfied. (iv) A route must not exceed a given time-span. In order to balance the route lengths, a route has to exceed a given minimization-time. If a satellite facility is already in a route, it cannot be reinserted in the same route. (v) All tractors are assigned to the central depot where they must return to after each route. Routes must start from and end at the central depot. Each tractor leaves from and returns to the depot exactly once. (vi) The TSRP deals with TL and does not consider cross-docking options.

The TSRP can be formulated as follows.

Let $G = (V, A)$ be a directed graph where $V = \{0, 1, 2, \ldots, n\}$ is the vertex set and $A = \{(i, j) \mid i, j \in V, i \neq j\}$, the arc set. Vertex 0 (v_0) is the central depot and the other vertices (v_i) in V (i.e., $V \setminus \{0\}$) correspond to satellite facilities. Loaded-semitrailer flows between any two terminals are R:

$$R = \begin{bmatrix} 0 & r_{01} & r_{02} & \cdots & r_{0n} \\ r_{10} & 0 & r_{12} & \cdots & r_{1n} \\ r_{20} & r_{21} & 0 & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{n0} & r_{n1} & \cdots & r_{n,n-1} & 0 \end{bmatrix}, \tag{1}$$

where r_{ij} denotes that there are r_{ij} loaded-semitrailers needed to be transported from v_i to v_j.

X^t_{ijk} and X^l_{ijk} are the decision variables. If the kth tractor runs from v_i to v_j, $X^t_{ijk} = 1$; otherwise, $X^t_{ijk} = 0$. If the kth loaded combination vehicle (i.e., the kth tractor pulling one loaded-semitrailer) runs from v_i to v_j, $X^l_{ijk} = 1$; otherwise, $X^l_{ijk} = 0$.

C^t_{ijk} is the fuel consumption of the kth tractor running from v_i to v_j. C^l_{ijk} is the fuel consumption of the kth loaded combination vehicle running from v_i to v_j. T^t_{ijk} is the running time of the kth tractor running from v_i to v_j and vel^t the average velocity. T^l_{ijk} is the running time of the kth loaded combination vehicle running from v_i to v_j and vel^l the average velocity. The tractor's on-duty hours per day is T_0.

The objective function is

$$\text{Min} \quad \gamma \cdot \frac{\left(\sum_i \sum_j \sum_k C^t_{ijk} X^t_{ijk} + \sum_i \sum_j \sum_k C^l_{ijk} X^l_{ijk}\right)}{\left(W \cdot \sum_k \sum_i \sum_j X^l_{ijk} \cdot T^l_{ijk} \cdot \text{vel}^l\right)} \tag{2}$$

The constraints are

$$\sum_k \sum_i \sum_j X^l_{ijk} \geq \eta \cdot \sum_i \sum_j r_{ij}, \tag{3}$$

$$\sum_k X^l_{ijk} \leq r_{ij}, \tag{4}$$

$$\sum_i X^t_{0ik} + \sum_i X^l_{0ik} = 1, \tag{5}$$

$$\sum_i X^t_{i0k} + \sum_i X^l_{i0k} = 1, \tag{6}$$

$$\left(\sum_i \sum_k X^t_{ij'k} + \sum_i \sum_k X^l_{ij'k}\right) - \left(\sum_i \sum_k X^t_{j'ik} + \sum_i \sum_k X^l_{j'ik}\right) = 0, \quad \left(j' = 1, 2, \ldots, n\right), \tag{7}$$

$$X^t_{ijk} + X^l_{ijk} \leq 1, \tag{8}$$

$$\sum_i \sum_k X^l_{i0k} - \sum_i \sum_k X^l_{0ik} = 0, \tag{9}$$

$$X^t_{ijk} + X^t_{jhk} \leq 1, \tag{10}$$

$$\sum_i \sum_j T^l_{ijk} \cdot X^l_{ijk} > \sum_i \sum_j T^t_{ijk} \cdot X^t_{ijk}, \tag{11}$$

$$t_H + T_{st} + \sum_i \sum_j \left(T^t_{ijk} \cdot X^t_{ijk} + T^l_{ijk} \cdot X^l_{ijk}\right) \geq \rho_1 \cdot T_0, \tag{12}$$

$$t_H + T_{st} + \sum_i \sum_j \left(T^t_{ijk} \cdot X^t_{ijk} + T^l_{ijk} \cdot X^l_{ijk}\right) \leq \rho_2 \cdot T_0. \tag{13}$$

$X^t_{ijk} \in \{0, 1\}$; $X^l_{ijk} \in \{0, 1\}$; $i, j, h = 0, 1, 2, \ldots, n$; $i \neq j$; $j \neq h$; k is an integer and the maximum k is the total of tractors used.

The objective function is the CO_2 emissions per ton-kilometer of the TSRP, where γ is the emission coefficient (a constant) and W the freight weight on a loaded-semitrailer.

Constraints (3) and (4) guarantee that the total freight flow demand is satisfied by a certain percentage (η, $0 < \eta \leq 1$), while the demand of any terminal is respected. Constraints (5) and (6) guarantee that any tractor starts from the central depot and terminates at the central depot. Constraints (7) guarantee that satellite facilities cannot reserve any tractor. Constraints (8) are the restrictions of the tractor (i.e., running-alone tractor and tractor attached in combination vehicle) passing by a certain arc. Constraints (9) guarantee the flow balance of the central depot. Constraints (10) forbid the illegal segments of routes. Constraints (11) guarantee the load-running rate of tractors.

Constraints (12) and (13) are the restrictions of balancing the route lengths, where ρ_1 ($0 < \rho_1 < 1$) and ρ_2 ($1 \leq \rho_2 \leq \tau$, τ is a limited number) are the lower and upper limits of the utilization ratio of the tractor's on-duty hours, respectively. t_H is the tractor's residence time at the central depot. T_{st} is the total of tractors' attach/detach time at satellite facilities. T_{st} is affected by the number of satellite facilities included in a route. When a route k' includes $f_{k'}$ satellite facilities and the tractor's attach/detach time at a satellite facility is t_{sf}, $T_{st} = f_{k'} \cdot t_{sf}$, where $f_{k'} = \sum_i \sum_j (X^t_{ijk'} + X^l_{ijk'}) - 1$.

Although the decision variables of the formulation are binary, the route is decided. Constraints (5)~(10) suggest that the route is made up of sequential arcs which are passed by the tractor or the loaded combination vehicle. We denote the terminal sequence of a route by $H - s_1 - \cdots - s_f - H$, where H is the central depot and s_i satellite facility.

Generally, efficient exact algorithms to solve the model we presented here for realistic problem sizes do not exist. Thus, such model can only be solved by heuristics to attain suboptimal solutions of a priori unknown quality. In such cases, it is useful to find lower bounds to get an estimate for the quality of the solution found by the heuristics. If the number of variables and constraints in a derivative model is significantly less than those in 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 [39]. If we relax the route length constraints (12) and (13) in the model above, the objective function and constraints (3)~(11) can be reformulated as another model (denoted as LBM) that can be solved on small-scale instances. The solution of LBM may also be the optimal solution of an instance if it satisfies the relaxed time-span constraints. We use this lower bound to compare the performance of the heuristics presented in Section 4.

In addition, the objective function of the TSRP model is substantially affected by two parts: one $(\sum_i \sum_j \sum_k C^t_{ijk} X^t_{ijk}) / (\sum_k \sum_i \sum_j X^l_{ijk} \cdot T^l_{ijk} \cdot \text{vel}^l)$ and the other $(\sum_i \sum_j \sum_k C^l_{ijk} X^l_{ijk}) / (\sum_k \sum_i \sum_j X^l_{ijk} \cdot T^l_{ijk} \cdot \text{vel}^l)$. When constraints (3) and (4) are equations and the satisfied demand percentage is 100%, the objective function is affected by the former part. If any segment on routes has loaded-semitrailer transported, that is, $X^t_{ijk} = 0$ for all i, j, and k, the objective function reaches the minimum. The minimum is suggested as a benchmark for LBM.

4. Heuristic Algorithm

Three types of algorithms are used to solve the VRP [40]. The first type consists of exact algorithms that are time-consuming. The second type consists of classical heuristics such as greedy, local search, and relaxation based. The third type consists of heuristics that are based on some metaheuristic rules. Such metaheuristics or framework for building heuristics are SA, Tabu search, Genetic algorithms, Variable neighborhood search, and so forth. The high computational cost of exact methods and their poor performance in large problems have involved that the current research concentrates on stochastic algorithms that are capable of producing feasible but not necessarily optimal solutions in limited time [5]. The SA algorithm is one of the commonly used metaheuristics, which has been successfully applied to solve several types of VRP. Motivated by the success of the SA for the TTRP (e.g., [26, 27]), we have therefore opted a heuristic algorithm based on the SA to solve the TSRP.

The SA uses a stochastic approach to search for and move to neighborhood solutions. If a better neighborhood solution is identified in the search starting from the current solution, the move will be accepted and the current solution will be replaced by the better neighborhood solution. The search for a better neighborhood solution then continues. Besides, the SA will accept the moving to a worse neighborhood solution with a certain probability to escape from a local optimum. The accepted probability is based on two parameters, the temperature which gradually reduces and the objective function difference between the two solutions. At the beginning of the search, the accepted probability of the move is higher. When nearing the end of the search process, the accepted probability of the move is smaller. Generally, the initial temperature, the cooling function, and the final temperature will affect the results of the SA.

4.1. The Neighborhood and Initial Solution. Braysy and Gendreau [41] stated that local search plays a very important role in the design of metaheuristics for the VRP. A local search operator iteratively improves a solution by exploring its neighborhood. The TSRP model suggests that the route is made up of sequential arcs. Any ones of the constraints of (5) to (10) guarantee some requirements for segments of a route, while the route length constraints (12) and (13) guarantee an entire requirement of a route. We regard constraints (12) and (13) as the most important factors to decide a solution's neighborhood.

The tractor's on-duty hours per day (T_0) depend on the on-duty hours of the driver team. A driver's on-duty hours (denoted by T_p) consist of driving hours, attach/detach time (t_{sf}) and residence time (t_H) at terminals. If the number of drivers allocated to each tractor is h, $T_0 = h \cdot T_p$. When the transporting distance between terminals v_i and v_j is d_{ij} and vel the average velocity, the running time between v_i and v_j is (d_{ij}/vel). Constraints (12) and (13) are rewritten as

$$\rho_1 \cdot h \cdot T_p \leq \sum_i \sum_j \left(\frac{d_{ij}}{\text{vel}} \right) + f_{k'} \cdot t_{sf} + t_H \leq \rho_2 \cdot h \cdot T_p. \quad (14)$$

The vehicle-kilometer (v-km) is the most important index for enterprises to evaluate the performance of vehicles and drivers. When there are $f_{k'}$ satellite facilities in a route, the more the $f_{k'}$, the slower the average velocity because the tractor/vehicle has to frequently enter into and depart off terminals where a slow velocity is allowed. The average velocity (denoted by $\mathrm{vel}(f_{k'})$) is regarded as a decreasing function. If the utilization ratio of the tractor's on-duty hours is 100%, the running time of the route is $(h \cdot T_p - f_{k'} \cdot t_{sf} - t_H)$. Then, the v-km of vehicles/drivers is $VK = \mathrm{vel}(f_{k'}) \cdot (h \cdot T_p - f_{k'} \cdot t_{sf} - t_H)$. The v-km will decrease along with increasing $f_{k'}$. Therefore, the routes include finite inserted satellite facilities. We enumerate the number of satellite facilities in a route to search entirely to find all routes that satisfy constraints (14). When the routes include at least 1 and at most $f_{k'}$ satellite facilities, there are $O(n^{f_{k'}})$ potential routes for selection, which also make up the neighborhood.

Unlike the VRP or the TTRP where every removal is accompanied by an insertion, one may decide removal and not continue an insertion in our problem. This partial solution will still be feasible when the demand satisfied percentage keeps larger than the minimum (η). By referring to the traditional destroy and repair framework, we take a whole route as the operator unit. There are three types of operators. (i) A route is removed from the current solution by a destroy operator. (ii) A route is removed from the current solution by a destroy operator and another route is reinserted by a repair operator. The removed route is recorded by the neighborhood and is still a candidate route of the repair operator. (iii) A route may clone itself several times. The times are decided by the maximum demand of satellite facilities included by the route. The clone operator is a special type of repair operator. The realistic-size instance results in Section 5 show the effect of the clone operator.

To the generation of the initial solution, our computational tests show a similar conclusion as that of Coelho et al. [42]. The initial solution does not have significant impacts on the overall solution cost or the running time. We therefore generate randomly the initial solution.

4.2. The SA Heuristic. The number of tractors (or the number of routes in the solution) is unknown, but it is an essential parameter at the beginning. It is likely that a tractor pulls more than one independent semitrailer on the route. Denoting the average number of transported loaded-semitrailers on a route as ξ, $(\sum_i \sum_j r_{ij})/\xi$ is an important benchmark of the number of tractors. The number of tractors should be limited integers. Our experimental results show that the CO_2 emissions per ton-kilometer can be decreased by adding or subtracting up to $(\sum_i \sum_j r_{ij})/(3 \cdot \xi)$ extra tractors. It is suggested that the SA heuristic for the TSRP does not take the number of tractors as one of the objective values. Meanwhile, the computational tests show that it is feasible for $\xi = 4$. The SA procedure is started by selecting randomly $N_0 = \lfloor(\sum_i \sum_j r_{ij})/4\rfloor$ routes as the initial solution where $\lfloor\bullet\rfloor$ denotes the largest integer which is smaller than or equal to the enclosed number. In each iteration, the objective function which is used to evaluate the sequential solutions is the percentage of satisfied freight demand. When the percentage of satisfied freight demand reaches η, the SA procedure finds a nondominated solution for the number of tractors. If the percentage of satisfied freight demand is less than η, the number of routes in the former solution (N_i) is enlarged by $(1 + \delta)$ times (where $0 < \delta < 0.05$) and the SA procedure started with $\lfloor N_i \cdot (1+\delta) \rfloor$ routes. Finally, the number of tractors is decided.

The SA procedure is run in two phases. In the first phase, a nondominated solution with the minimum number of tractors is obtained. In the second phase, successively CO_2 emissions per ton-kilometer are minimized for the current number and for the number of tractors which is increased by one every time until a predefined stopping criterion is met (e.g., the CO_2 emissions per ton-kilometer stop decrease).

The initial temperature, the final temperature, the Boltzmann constant used in the probability function, the maximum number of iterations, and the cooling mechanism adjusted by the number of iterations are made certain firstly. The probability function used for the SA procedure deciding the number of tractors is different from that for the SA procedure deciding the final solution of the TSRP. The former mainly considers the percentage of satisfied freight demand, while the latter considers synchronously the percentage of satisfied freight flow demand and the CO_2 emissions per ton-kilometer. As proposed by Kuo [9], our SA model also involves the temperature being cooled each iteration, which is different from general SA where a certain number of iterations take place between each cooling. We use an initial temperature of 100, a final temperature of 1 and the number of iterations in the SA equals to 100000 (for the small-scale random instances of the next section) or 4500000 (for the realistic instance of the next section). The cooling mechanism is adjusted based on the number of iterations. The termination condition is to stop the algorithm when the number of iterations reaches its maximum and the temperature becomes 1.

5. Computational Study

Since we are not aware of any prior test instance for the TSRP minimizing CO_2 emissions per ton-kilometer, the proposed model and algorithm were tested on a range of small-scale instances generated randomly and a realistic instance. Our computational experiments were carried out in two parts. First, the small-scale instances were used to show the effectivity of our model and the heuristic. We have also calibrated the solution methods on small-scale instances as explained in Section 5.1. Second, we have run the heuristic on a realistic instance with varying central depot location as explained in Section 5.2. The emphasis lies on summing some calibrating methods to seek a closely parameter-free metaheuristic by small-scale instances generated randomly. Referring to calibrating methods, the SA heuristic algorithm can generate high-quality solutions in relatively little time with some parameter tuning.

5.1. Small-Scale Instances. The proposed TSRP model and the SA heuristic are assessed on a number of small-scale test problems on 5×5 grid graphs. Several parameters are considered while the problems are created (1) the number of satellite facility nodes (C_n); (2) the number of loaded-semitrailers of each satellite facility; (3) the location of the central depot; (4) the location of the satellite facilities; (5) the parameters of tractors and semitrailers (e.g., fuel consumption, cargo weight of a loaded-semitrailer, velocity, etc.); (6) the distance between any two nodes; (7) the distance span of a route.

The small-scale instances are divided into four sets according to the number of satellite facilities. The small-scale instances are created by a random fashion as follows. The "RANDOM" function in Matlab is used. By RANDOM ("norm",1,1,5,5), random arrays are generated. We select the minimum position of a random array as the central depot and other C_n negative positions of the array satellite facilities. The distance between any two terminals is calculated by the gaps of rows and columns. The "RANDOM" function is used ten times and each set includes ten instances. The "RANDOM" function is also used to determine the number of loaded-semitrailers of terminals.

The tractor-semitrailer combination, which can load maximally 30 tons and satisfies the fuel-efficiency requirements of "Regulation of Supervising Vehicle Fuel Consumption" (number 11/2009 Decree of Ministry of Transport of the People's Republic of China (MOTPRC)), is used to transport goods. The type code of the selected combination is "CQ4254HTVG324V" or "ND4251B32J7." The fuel consumption is 18 liters diesel per 100 kilometers for a tractor running alone and 32 liters diesel per 100 kilometers for a combination run. Suppose that: the gap between adjacent rows or columns of the random array is 50 km; the loading factor of loaded-semitrailer is 60%; the velocity is 50 km/h; the distance span is around 650 km; and the percentage of satisfied freight demand is not less than 85%.

The test problems are detailed in Table 1. Columns 1–9 indicate the test problem, the rectangle region, the total number of loaded-semitrailers, the average loaded-semitrailer number of all satellite facilities, the variance of loaded-semitrailer number of all satellite facilities, the minimum distance between central depot and satellite facility, the maximum distance between central depot and satellite facility, the average distance between any two terminals and the variance of distances between any two terminals respectively.

To obtain lower bounds, the integer programming model (LBM) presented in Section 3 has been implemented and solved using LINGO11. The solving course of LBM took the number of tractors as a precondition; that is, $k = \lfloor (\sum_i \sum_j r_{ij})/4 \rfloor$. When computing the lower bound LBM for an instance, we may find a better value of k during the computational experiments. In course of finding feasible solution for LBM, the number of tractors is adjusted manually. Besides, the proposed SA algorithm has been coded in MATLAB R2010b and run on a computer with an AMD Athlon(tm) X2 Dual-Core QL-65 running at 2.10 GHz under Windows 7 ultimate (32 bits) with 2 GB of RAM. The computational results are presented in Table 2.

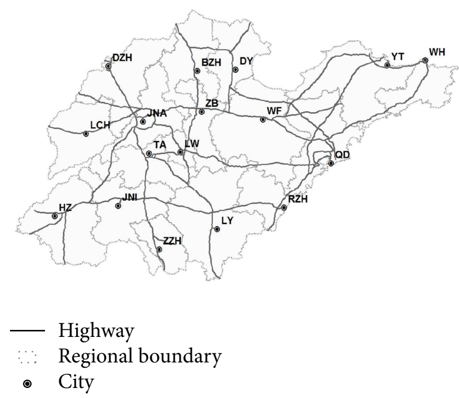

Figure 1: A sketch map of city location and highway infrastructure in Shandong province of China.

When there idealistically exists a situation in which the distribution of terminals and the loaded-semitrailer flows right satisfy all constraints so that any segment on routes has loaded-semitrailer transported, the CO_2 emissions per ton-kilometer will reach the minimum. According to our assumption, the minimum is 48.53 g CO_2/t-km. Since most instances can hardly satisfy the idealistical requirement, the CO_2 emissions per ton-kilometer of the LBM will be larger than 48.53 g CO_2/t-km. We calculate the percentage gap by $gap_1 = |(\text{LBM} - \text{Min})/\text{Min}| \times 100$ or $gap_2 = |(\text{SA} - \text{LBM})/\text{LBM}| \times 100$. The results show that the average percentage gap between LBM and the theoretical minimum is 4.72%. 72.5% of the 40 test instances have percentage gaps of lower than 5%.

As showed in Table 2, the solution CO_2 emissions per ton-kilometer obtained by the proposed SA heuristic are close to the lower bound. For some instances, such as RAND5-4, RAND5-8, RAND6-8, RAND7-1, RAND7-2, RAND7-4, RAND7-6, and RAND8-1, the gaps between the heuristic solution and LBM are less than 1%. For all 40 test instances, the largest percentage gap between the heuristic solution and LBM is 14.20%, and the average percentage gap is 2.79%. 87.5% of the 40 instances have percentage gaps of lower than 5%.

It is worth noting that the location of a central depot likely affects the percentage gap. The instances with percentage gaps of over 5% have their central depots located alongside the boundary of the regions.

5.2. A Realistic Instance. The main purpose of the realistic instance study is to evaluate the applicability of the developed heuristics for realistic-size problems.

A trucking company in Shandong province of China, simply named SDEXP, is the object of our computational study. SDEXP comprises 17 affiliates distributed in 17 cities of Shandong province (Figure 1). SDEXP employed hundreds of single-unit trucks to transport cargoes before 2007 and had a road freight market share of about 1.25% in Shandong

Table 1: Basic characteristics of the 40 test problems.

Problem	Region (km × km)	Freight flow demand (loaded-semitrailer)			Distance between central depot and satellite facility		Distance between any two terminals	
		Total	Average	Variance	Min.	Max.	Average	Variance
RAND5-1	200 × 150	49	2.5	1.0	50	200	126.7	2712.6
RAND5-2	200 × 200	51	2.6	1.0	50	200	133.3	2298.9
RAND5-3	250 × 200	60	2.4	1.1	50	200	163.3	4988.5
RAND5-4	200 × 200	58	2.9	0.8	50	200	133.3	2298.9
RAND5-5	200 × 250	46	2.3	1.1	50	250	176.7	7195.4
RAND5-6	200 × 200	66	2.6	0.9	50	150	143.3	3057.5
RAND5-7	250 × 250	57	2.3	1.0	50	300	186.7	7402.3
RAND5-8	200 × 250	74	2.5	1.0	50	300	173.3	6160.9
RAND5-9	200 × 250	70	2.3	1.0	200	350	183.3	6781.6
RAND5-10	250 × 150	81	2.3	1.2	50	200	123.8	3809.5
RAND6-1	200 × 250	74	2.5	1.0	50	300	173.3	6160.9
RAND6-2	200 × 200	99	2.8	1.3	50	250	147.6	4994.2
RAND6-3	200 × 250	91	2.5	1.2	50	200	161.9	5342.6
RAND6-4	200 × 250	72	2.4	0.9	50	200	138.1	4854.8
RAND6-5	250 × 150	73	2.4	0.9	50	250	142.9	4947.7
RAND6-6	250 × 250	97	2.7	0.9	100	200	185.7	6132.4
RAND6-7	200 × 200	99	2.8	1.3	50	250	147.6	4994.2
RAND6-8	250 × 200	80	2.7	1.0	50	250	161.9	6806.0
RAND6-9	250 × 200	98	2.7	1.1	50	300	142.9	4703.8
RAND6-10	150 × 250	106	2.9	0.7	50	250	138.1	4854.8
RAND7-1	200 × 200	102	2.4	1.1	50	200	132.1	3675.3
RAND7-2	250 × 250	74	2.1	0.8	100	250	176.8	6633.1
RAND7-3	250 × 250	109	2.6	0.9	100	300	162.5	5022.7
RAND7-4	250 × 200	88	2.5	1.3	100	200	155.4	5152.6
RAND7-5	250 × 250	74	2.1	0.8	100	300	176.8	6633.1
RAND7-6	250 × 250	74	2.1	0.8	100	300	176.8	6633.1
RAND7-7	250 × 250	74	2.1	0.8	100	200	176.8	6633.1
RAND7-8	250 × 250	74	2.1	0.8	100	300	176.8	6633.1
RAND7-9	250 × 250	74	2.1	0.8	150	250	176.8	6633.1
RAND7-10	250 × 250	74	2.1	0.8	100	400	176.8	6633.1
RAND8-1	200 × 250	126	2.6	1.2	50	300	141.7	4436.6
RAND8-2	200 × 250	126	2.6	1.2	50	250	141.7	4436.6
RAND8-3	200 × 250	126	2.6	1.2	50	150	141.7	4436.6
RAND8-4	200 × 250	126	2.6	1.2	50	150	141.7	4436.6
RAND8-5	200 × 250	126	2.6	1.2	50	200	141.7	4436.6
RAND8-6	200 × 250	126	2.6	1.2	150	300	141.7	4436.6
RAND8-7	200 × 250	126	2.6	1.2	50	200	141.7	4436.6
RAND8-8	200 × 250	126	2.6	1.2	50	250	141.7	4436.6
RAND8-9	200 × 250	150	3.1	0.8	100	350	163.9	5438.2
RAND8-10	200 × 250	150	3.1	0.8	100	350	163.9	5438.2

Note: the problem is denoted by RAND (number 1)-(number 2) where number 1 is the number of satellite facilities and ranges from 5 to 8, and number 2 is the instance sequence in a same set.

Table 2: Computational results for the 40 test problems.

Problem	SA			LBM			gap1 (%)	gap2 (%)
	Percentage of satisfied freight demand (%)	Tractor quantity	CO_2 emissions per ton-kilometer (g/tm)	Percentage of satisfied freight demand (%)	Tractor quantity	CO_2 emissions per ton-kilometer (g/tm)		
RAND5-1	86	13	51.85	86	12	50.39	3.83	2.90
RAND5-2	86	14	54.65	86	12	49.01	0.99	11.51
RAND5-3	87	12	49.99	87	15	49.16	1.30	1.69
RAND5-4	88	16	49.99	86	15	50.27	3.59	0.56
RAND5-5	89	10	57.33	87	12	50.20	3.44	14.20
RAND5-6	88	15	50.56	88	17	49.85	2.72	1.42
RAND5-7	88	13	49.97	86	14	49.13	1.24	1.71
RAND5-8	86	16	50.74	87	19	50.78	4.64	0.08
RAND5-9	89	14	50.77	89	18	51.29	5.69	1.01
RAND5-10	85	14	49.17	85	20	50.14	3.32	1.93
RAND6-1	85	14	48.95	85	19	50.35	3.75	2.78
RAND6-2	90	19	48.92	89	25	49.86	2.74	1.89
RAND6-3	86	18	50.13	86	23	50.79	4.66	1.30
RAND6-4	86	17	49.97	86	18	48.89	0.74	2.21
RAND6-5	89	14	48.71	88	18	49.22	1.42	1.04
RAND6-6	86	16	48.70	86	24	50.25	3.54	3.08
RAND6-7	90	17	48.82	89	25	49.86	2.74	2.09
RAND6-8	88	17	49.82	86	20	49.50	2.00	0.65
RAND6-9	90	17	48.64	89	25	49.95	2.93	2.62
RAND6-10	88	18	48.73	86	27	50.35	3.75	3.22
RAND7-1	90	21	49.84	88	26	50.12	3.28	0.56
RAND7-2	86	17	50.37	87	19	50.59	4.24	0.43
RAND7-3	90	18	49.13	89	27	54.03	11.33	9.07
RAND7-4	86	19	49.72	85	22	50.05	3.13	0.66
RAND7-5	85	16	52.36	85	16	53.08	9.38	1.36
RAND7-6	85	14	51.95	85	12	51.81	6.76	0.27
RAND7-7	85	14	52.08	85	14	53.17	9.56	2.05
RAND7-8	85	16	52.77	85	16	53.79	10.84	1.90
RAND7-9	85	13	54.79	88	13	53.58	10.41	2.26
RAND7-10	85	16	55.69	85	15	53.04	9.29	5.00
RAND8-1	86	21	49.49	86	32	49.74	2.49	0.50
RAND8-2	88	24	52.82	89	13	49.57	2.14	6.56
RAND8-3	89	24	51.35	89	26	50.62	4.31	1.44
RAND8-4	88	24	51.68	89	20	50.17	3.38	3.01
RAND8-5	88	23	50.83	88	24	50.51	4.08	0.63
RAND8-6	89	22	54.88	89	22	53.96	11.19	1.70
RAND8-7	88	22	53.04	89	22	50.33	3.71	5.38
RAND8-8	87	22	52.82	87	26	50.84	4.76	3.89
RAND8-9	87	27	49.99	87	38	52.05	7.25	3.96
RAND8-10	87	26	50.95	87	36	52.61	8.41	3.16

province. Along with the policy on encouraging and popularizing tractor and semitrailer combinations issued by the MOTPRC during the 11th five-year plan period (2006~2010), SDEXP plans to gradually substitute tractor and semitrailer combinations for single-unit trucks.

We abstract the transportation network of SDEXP on a graph, where the nodes denote the cities and the arcs denote road infrastructure connecting every two cities. Suppose any city node can be regarded as a central depot and other city nodes satellite facilities. Table 3 gives the distances between

Table 3: The distances between any two cities (km).

	JNA	QD	ZB	ZZH	DY	YT	WF	JNI	TA	WH	RZH	LW	LY	DZH	LCH	BZH	HZ
JNA	0	361	111	245	225	457	209	202	75	517	332	86	250	131	125	159	251
QD	361	0	263	429	275	251	157	448	363	272	175	308	300	469	464	330	557
ZB	111	263	0	313	128	360	112	270	146	419	323	91	240	222	216	83	357
ZZH	245	429	313	0	439	589	424	137	172	649	267	222	116	329	324	372	247
DY	225	275	128	439	0	350	141	398	274	410	359	219	368	335	329	75	470
YT	457	251	360	589	350	0	252	606	504	65	333	449	458	565	559	426	700
WF	209	157	112	424	141	252	0	382	257	314	226	202	249	318	313	179	454
JNI	202	448	270	137	398	606	382	0	130	667	285	180	203	287	156	331	126
TA	75	363	146	172	274	504	257	130	0	566	277	58	195	169	163	207	240
WH	517	272	419	649	410	65	314	667	566	0	395	510	519	626	621	487	762
RZH	332	175	323	267	359	333	226	285	277	395	0	247	137	443	437	383	395
LW	86	308	91	222	219	449	202	180	58	510	247	0	165	225	220	152	290
LY	250	300	240	116	368	458	249	203	195	519	137	165	0	361	355	301	313
DZH	131	469	222	329	335	565	318	287	169	626	443	225	361	0	180	271	338
LCH	125	464	216	324	329	559	313	156	163	621	437	220	355	180	0	263	225
BZH	159	330	83	372	75	426	179	331	207	487	383	152	301	271	263	0	404
HZ	251	557	357	247	470	700	454	126	240	762	395	290	313	338	225	404	0

Table 4: The freight flows between two cities (unit: loaded-semitrailer).

To	From																
	JNA	QD	ZB	ZZH	DY	YT	WF	JNI	TA	WH	RZH	LW	LY	DZH	LCH	BZH	HZ
JNA	0	1	2	1	2	1	3	1	0	0	0	0	1	0	1	2	1
QD	1	0	6	0	4	6	17	0	1	2	3	1	2	1	1	1	0
ZB	1	4	0	1	2	2	3	1	1	1	0	0	2	3	3	0	1
ZZH	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
DY	2	3	2	0	0	1	1	0	1	0	0	0	1	1	1	0	0
YT	1	6	2	0	2	0	4	0	0	1	1	0	1	0	0	0	0
WF	3	14	3	0	1	4	0	0	1	1	1	1	2	1	1	3	0
JNI	1	0	1	0	0	0	0	0	0	0	0	0	1	0	2	0	0
TA	0	1	1	1	1	0	1	0	0	0	0	0	2	2	3	1	1
WH	0	2	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0
RZH	0	3	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
LW	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	1	0
LY	1	2	3	0	1	1	2	1	2	0	0	1	0	0	0	1	0
DZH	0	0	3	0	1	0	1	1	2	0	0	0	0	0	2	1	0
LCH	1	1	3	0	1	0	1	2	2	0	0	1	0	2	0	1	1
BZH	2	1	0	0	0	0	4	0	1	0	0	1	1	1	1	0	0
HZ	1	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0

every two cities. SDEXP's expected freight flows between any two cities per day are given in Table 4.

The tractor-semitrailer combination adopted in the small-scale instances is used in the realistic instance. Suppose that the loading factor of loaded-semitrailer is 50%; the velocity is 80 km/h; and the percentage of satisfied freight flow demand is not less than 80%. The fuel consumption is 17 liters diesel per 100 kilometers for a tractor that runs alone and 40 liters diesel per 100 kilometers for a combination runs. The distance span is affected by drivers' on-duty time. According to SDEXP experience, a driver's average on-duty time is 8.5 hours per day. A tractor with two drivers can work consecutively for not more than 17.0 hours in a 24-consecutive-hour period. The attach/detach time at satellite facilities is 2/3 hour, and the residence time in the central depot is 2 hours. $\rho_1 = 0.9$. $\rho_2 = 1.1$.

Supposing any one of the 17 cities the candidate central depot city for SDEXP, there are 17 scenarios classified by the location of the central depot. The satisfactory solutions of the 17 scenarios are in Table 5. When cities located in different spatial zone and having various freight flows are, respectively, regarded as the central depot, the performance of the satisfactory solution varies obviously. We use "Tractor quantity," "Percentage of fuel consumption for tractor

Table 5: The results of the 17 scenarios of the realistic instance.

The central depot city	Tractor quantity	Percentage of satisfied freight demand (%)	Average number of loaded-semitrailer on a route	Average distance span (km)	Percentage of fuel consumption for tractor running alone (%)	CO_2 emissions per ton-kilometer (g/tm)
JNA	52	82	4.20	1068	7.20	78.45
JNA*	62	80	3.44	1000	9.04	80.04
QD	44	81	4.93	1102	1.52	73.92
QD*	52	80	4.12	1036	3.75	75.64
ZB	52	81	4.12	1068	3.61	75.53
ZB*	55	81	3.93	1033	4.54	76.27
ZZH	76	80	2.82	1288	28.60	101.96
DY	56	80	3.82	1077	7.34	78.57
DY*	59	80	3.63	1045	8.39	79.47
YT	99	80	2.16	1082	32.66	108.11
WF	49	81	4.43	1047	1.48	73.89
WF*	51	80	4.20	1017	2.47	74.65
JNI	77	80	2.77	1159	27.06	99.81
TA	62	81	3.46	974	8.68	79.72
TA*	64	82	3.39	1010	10.05	80.93
WH	102	80	2.09	1382	43.02	127.76
RZH	72	81	2.99	1074	18.42	89.24
LW	61	81	3.52	1003	8.29	79.38
LW*	63	81	3.41	1026	10.03	80.91
LY	65	82	3.35	1075	15.02	85.67
LY*	67	81	3.21	1065	16.09	86.76
DZH	68	82	3.19	1121	19.07	89.95
LCH	64	80	3.33	1093	15.71	86.37
BZH	57	81	3.77	1028	6.61	77.95
BZH*	59	81	3.64	1023	7.82	78.98
HZ	77	80	2.77	1328	30.78	105.17

*The results without clone operator.

running alone," and "CO_2 emissions per ton-kilometer" to analyze the performance of the solutions.

At an approximative level of the percentage of satisfied freight demand, the needed quantity of tractors is about 64 for different central depot location except YT and WH. The average quantity of tractors is around 1/4 of total freight demand.

There exists a relationship between the quantity of needed tractors and the average loaded-semitrailer number of a route. Since the number of loaded-semitrailers is decided by the percentage of satisfied freight demand, the less the tractor number (or the route number), the more the loaded semi-trailer on a route. When the number of loaded-semitrailers and the distance span are decided, the more the tractor number, the more the percentage of fuel consumption for tractor running alone. The results are accordant with the above two relationships (Figure 2). The SA heuristics is stable to solve the realistic instance.

According to the methodology and factors developed by the Intergovernmental Panel on Climate Change (IPCC), CO_2 emissions are in direct proportion to fuel consumption, so CO_2 emissions of the solutions can express the variable cost of transportation. Escobar et al. [43] and Hashemi and Seifi [39] pointed that the transportation costs are often influenced by the decision of locating a depot and vice versa. Our results show a similar conclusion. The solutions for various central depot cities have different CO_2 emissions per ton-kilometer. Central depot cities located near the center of the research spatial scope (e.g., TA, LW, JNA, and ZB) have relatively good solutions. Besides, central depot cities located along Jinan-Qingdao Highway (JNA-ZB-WF-QD line) have good solutions that include more loaded-semitrailers on a route and a low level of CO_2 emissions per ton-kilometer. In fact, the transportation economic belt along Jinan-Qingdao Highway contributed around 40% of Shandong GDP and over 30% of Shandong road freight volume in the recent 5 years. It is implied that the CO_2 emissions per ton-kilometer of the solutions for different central depot cities are affected not only by central depot locations but also by transportation flows from economic relations.

There are estimation results of CO_2 emissions per ton-kilometer for various countries. For example, Ierland et al.

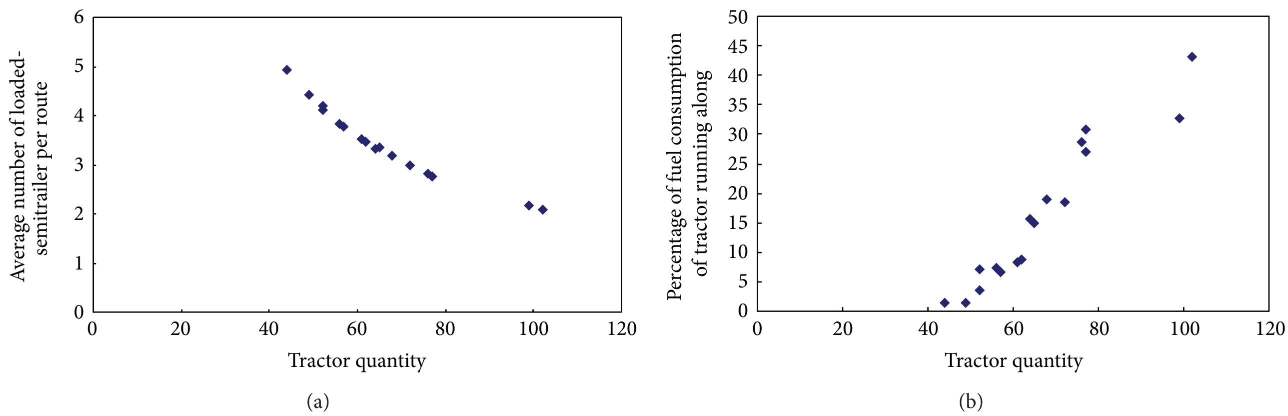

FIGURE 2: In the SA results, (a) the relationship between the tractor quantity and the average loaded-semitrailer number of a route; (b) the relationship between the tractor quantity and the percentage of fuel consumption for tractor running alone.

[13] noted that the CO_2 emission factor for trucks was 155 g CO_2/t-km in the Netherlands; European Environment Agency [44] noted that the average CO_2 emissions were 62~110 g CO_2/t-km for road transportation in EU Member States; Li et al. [3] noted that the average CO_2 emissions fluctuated between 100 g CO_2/t-km and 132 g CO_2/t-km from 1985 to 2007 in China. We have investigated some point-to-point haulages of SDEXP in 2009 and found that the CO_2 emission factor ranged from 100 g CO_2/t-km to 180 g CO_2/t-km, and the average was 135 g CO_2/t-km. Our realistic-instance study shows that the vehicle scheduling provided by the TSRP is promising to reduce road freight transportation CO_2 emissions.

The results are helpful and meaningful for SDEXP to select the location of the central depot, to configure tractors and the routes, and to reduce CO_2 emissions.

6. Conclusions and Future Work

This paper discussed the tractor and semitrailer routing problem and its mitigation effect of CO_2 emissions, which are promising with applications in multilevel freight distribution systems and full truckload to road freight-related CO_2 emissions reduction. A mathematical programming model with the objective of minimizing CO_2 emissions per ton-kilometer is presented for the tractor and semitrailer routing problem with full truckloads between any two terminals of the network. The SA heuristic is put forward to solve this problem of a realistic size. To validate the proposed heuristic, a lower bound is designed. The heuristic algorithm is tested on different types of problems. The results show that the proposed heuristic provides high-quality solutions in a reasonable computing time. The impact of the central depot location and the freight flow distribution on the solution quality is also explored. In conclusion, the proposed algorithm can provide robust solutions.

For future research, it would be interesting to test the effectiveness and efficiency of the proposed TSRP model and its solution approach on various practical examples. Some efficient heuristics for the TSRP may also be proposed. Besides, attentions can be focused on the extension of the TSRP, for example, TSRP with time windows and TSRP with vehicle routing of other levels of freight distribution system, which are properly of critical importance to the practical viability.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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