TIME-DEPENDENT ROUTING OF DRAYAGE OPERATIONS IN THE SERVICE AREA OF INTERMODAL TERMINALS

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ABSTRACT
In this paper the operational planning of drayage operations in the service area of intermodal terminals is studied. Drayage operations are the full truckload and empty container transport activities between container terminals, container depots, consignees and shippers. Most existing models consider travel times to be constant over time. In reality travel times depend on the time of the day. In this paper, time-dependent travel times are considered while planning daily drayage operations. A deterministic annealing meta-heuristic is proposed to solve the problem. The algorithm provides high quality results. Finally, two approaches to reduce computation time are presented.

Keywords: intermodal terminals, drayage operations, time-dependent travel times, vehicle routing

1. INTRODUCTION
Drayage operations refer to the full truckload container transport activities that take place on a regional scale around the intermodal container terminals. They involve the transport of loaded and empty containers between these container terminals, container depots, consignees and shippers. Drayage operations are mostly performed by truck and constitute a large part of total costs of an intermodal transport. Therefore, efficient planning of these operations is an important task. Special attention should be paid to minimizing empty container movements since these are costly activities which do not generate any revenue.

Often a sequential planning approach is proposed to plan daily drayage operations. First, an empty container allocation model is used to determine the optimal distribution of empty containers in the region, based on supply and demand information of consignees and shippers respectively. Next, a vehicle routing problem is solved to create efficient vehicle routes performing loaded and empty container transports. Recently, efforts to integrate both planning steps are introduced by several authors (Smilowitz 2006; Ileri 2006; Zhang, Yun, and Moon 2009; Zhang, Yun, and Kopfer 2010; Braekers, Caris, and Janssens 2012). In an integrated planning approach empty container allocation decisions are not taken in advance. Instead, these decisions are taken simultaneously with vehicle routing decisions. As a result, drayage costs may be reduced (Braekers, Caris, and Janssens 2012). Therefore, in this paper an integrated planning approach is used.

The majority of papers on the operational planning of drayage operations, like the ones mentioned above, make the simplifying assumption that travel times between locations are constant and only depend on the distance to be travelled. This is a very common assumption in vehicle routing literature. However, in reality travel times are not solely a function of the distance. Rather they will vary from time to time. Several causes of these variations in travel times may be identified. A major cause is the temporal variation in traffic density. Average traffic volumes are affected by hourly, daily, weekly and seasonal influences. Traffic density will be higher during peak hours than during non-peak hours while holidays and specific events may result in daily or weekly variations. Other causes of travel time variation include stochastic or unforeseeable events like accidents, vehicle breakdowns and weather conditions. (Malandraki and Daskin 1992; Balseiro, Loiseau, and Ramonet 2011) Neglecting the time-dependency of travel times may seriously affect the applicability of vehicle routing models in practice, especially when time windows at customers are involved and vehicle movements are planned in heavily congested areas (Hill and Benton 1992).

In this paper, the effect of hourly variations in travel times on the operational planning of drayage operations is studied. Travel times are assumed to be a deterministic function of the distance and the time of the day. This means that although travel times are not constant during the planning period, travel times at each point in time are known in advance. As a result, a deterministic planning approach may be used. Travel time variations due to random events like weather conditions and accidents are not considered. To take these variations into account, a stochastic approach should be considered.

Related literature is reviewed in Section 2. In Section 3, a detailed problem description is presented. A time-dependent version of the deterministic annealing algorithm for the integrated drayage problem presented in Braekers, Caris, and Janssens (2012) is introduced in Section 4. Results on randomly generated problem instances are discussed in Section 5. Finally, Section 6 contains conclusions and opportunities for further research.

2. LITERATURE REVIEW

In this section, an overview of literature on time-dependent vehicle routing is presented. For a detailed review of literature on drayage operations, the reader is referred to Braekers, Caris, and Janssens (2012).

Vehicle routing with time-dependent travel times is a relatively new research direction. The first steps to account for time-dependency of travel times in vehicle routing problems are presented by Hill and Benton (1992) and Malandraki and Daskin (1992). Hill and Benton (1992) propose to calculate time-dependent travel times on a link by using the average of speed levels in the area of the origin and destination. Malandraki and Daskin (1992) propose to use stepwise functions for modelling travel time variations. The planning period is divided in a number of intervals and the travel time on a link differs from interval to interval. As a result, the travel time on a link makes a jump at discrete moments in time. A major drawback of these early approaches is that they violate the non-passing or FIFO ('First-In-First-Out) property. This property encompasses the common sense idea that when a vehicle leaves node i for node j at a given time, any identical vehicle that leaves node i at a later time, cannot arrive earlier at node j. (Ahn and Shin 1991, Malandraki and Dial 1996).

Fleischmann, Gietz, and Gnutzmann (2004) describe a method to exclude the possibility of passing. The authors propose to remove the discrete jumps in stepwise travel time functions by smoothing the function. This smoothing relies on two parameters that have to be set appropriately. The resulting smoothed travel time function satisfies the non-passing property as long as the slope of the function is larger than minus one at any point (Fleischmann, Gietz, and Gnutzmann 2004; Kuo, Wang, and Chuang 2009). Another method to ensure the non-passing property is presented by Ichoua, Gendreau, and Potvin (2003). The authors propose to use a stepwise function for travel speed instead of a stepwise function for travel time. This means that the speed on a link changes at discrete points in time. It is easy to see that this method satisfies the non-passing property since at any time all vehicles travelling along an arc will have the same speed no matter where they are.

Recently, time-dependency of travel times in vehicle routing problem has received increased research attention. All recent papers consider travel times that satisfy the non-passing property.

To the authors' knowledge, only Namboothiri and Erera (2004) deal with time-dependent travel times in drayage operations. The authors study a drayage problem involving the transport of loaded containers between customers and a single terminal at the port. Delays at the terminal due to congestion are the only source of time-dependency of travel times. Exact and heuristic column generation approaches are proposed to solve the problem.

Other research on time-dependent vehicle routing has mainly focused on the Time-Dependent Vehicle Routing Problem (TD-VRP) and its variant where time windows at customers are imposed (TD-VRPTW). Exact approaches for the TD-VRPTW are proposed by Soler, Albiach, and Martinez (2009) and Dabia, Ropke, and Van Woensel (2011). Soler, Albiach, and Martinez (2009) describe a method to transform the problem to an asymmetric capacitated vehicle routing problem which may be solved exactly for small problem instances. Dabia, Ropke, and Van Woensel (2011) present a column generation approach embedded in a branch and cut framework. Due to the complexity of the problems, most research has focused on the development of (meta)-heuristics. Kuo, Wang, and Chuang (2009) and Jabali et al. (2009) propose tabu search algorithms for the TD-VRP. Jung and Haghani (2001) and Haghani and Jung (2005) present a genetic algorithm on the dynamic time-dependent vehicle routing problem with mixed linehauls and backhauls. Hashimoto, Yagiura, and Ibaraki (2008) discuss an iterated local search algorithm for the TD-VRPTW. Ant colony system algorithms for this problem are proposed by Donati et al. (2008) and Balseiro, Loiseau, and Ramonet (2011). Figliozzi (2012) proposes a solution algorithm based on a route construction and route improvement heuristic while Kok, Hans, and Schutten (2011) study a TD-VRPTW where driving regulations are imposed. Finally, vehicle routing problems with stochastic time-dependent travel times are studied by Van Woensel et al. (2007, 2008) and Lecluyse, Van Woensel and Peremans (2009).

3. PROBLEM DESCRIPTION

The problem studied in this paper is to construct efficient vehicle routes performing all loaded and empty container transports during a single day in the service area of one or more intermodal container terminals. Only full truckload container transports are considered.

A loaded container transport represents a full truckload transport from a shipper to a container terminal (outbound loaded container) or from a container terminal to a consignee (inbound loaded container). For each container, the terminal to be used is predefined so that for all loaded container transports the origin and destination are known in advance. Time windows are imposed on these transport tasks.

For empty container transports, either the origin or the destination is not defined in advance. A shipper may request an empty container to be delivered before a specific point in time. The origin of this empty container is irrelevant for the shipper and can be chosen by the decision maker. On the other hand, a consignee will have an empty container available after unloading an inbound loaded container. This container becomes available at a certain point in time and should be picked up before the end of the day. The destination of the empty container is determined by the decision maker. Empty containers can thus be transported from consignees to container terminals, from container terminals to shippers or directly from consignees to shippers.

A homogeneous fleet of vehicles with a single container capacity is assumed. All vehicles start and end their route at the vehicle depot. When a vehicle arrives early at a location, waiting is allowed at no cost. The service time to pickup and drop off containers is constant and the same for loaded and unloaded containers. A hierarchical objective function is used. The primary objective is to minimize the number of vehicles used while the secondary objective is to minimize total route duration (sum of travel, service and waiting times).

An example of a small problem is shown in Figure 1a. The problem consists of a single vehicle depot, two container terminals, an inbound loaded container transport task, an outbound loaded container transport task, an empty container supply location and an empty container demand location. When no time windows are imposed, Figure 1b shows the optimal solution for this problem. A single vehicle is used to execute all transportation tasks. First, the vehicle performs the inbound loaded container transport task. Second, an empty container is transported directly from the empty container supply location to the empty container demand location. Finally, the vehicle performs the outbound loaded container transport task before returning to the vehicle depot.

Time-dependent travel times are calculated using the method of Ichoua, Gendreau, and Potvin (2003). The eight hour planning period is divided in five intervals. For each link in the network, a speed distribution over all five intervals is defined. In literature, often different speed levels are assigned to different (types of) links in the network. In our opinion this requires a good understanding of the different types of links and the extent to which they are subject to congestion. This may be the case when working with travel speeds on an actual road network. On the other hand, (randomly) assigning speed distributions to links might not make much sense when working with problem instances which are randomly generated on a Euclidean plane like here. Therefore, in this work the assumption is made that the whole region in which drayage operations take place is equally affected by congestion during peak hours. This means that all links in the network have the same speed distribution. A similar approach is considered by Jabali et al. (2009) and Figliozzi (2012). Speed during the first, third and fifth interval is assumed to be 60 kilometres per hour while speed drops to 36 kilometres per hour due to congestion during periods two and four. An overview of the speed distribution and the corresponding travel times on a link of 20 kilometres is shown in Figures 2 and 3.

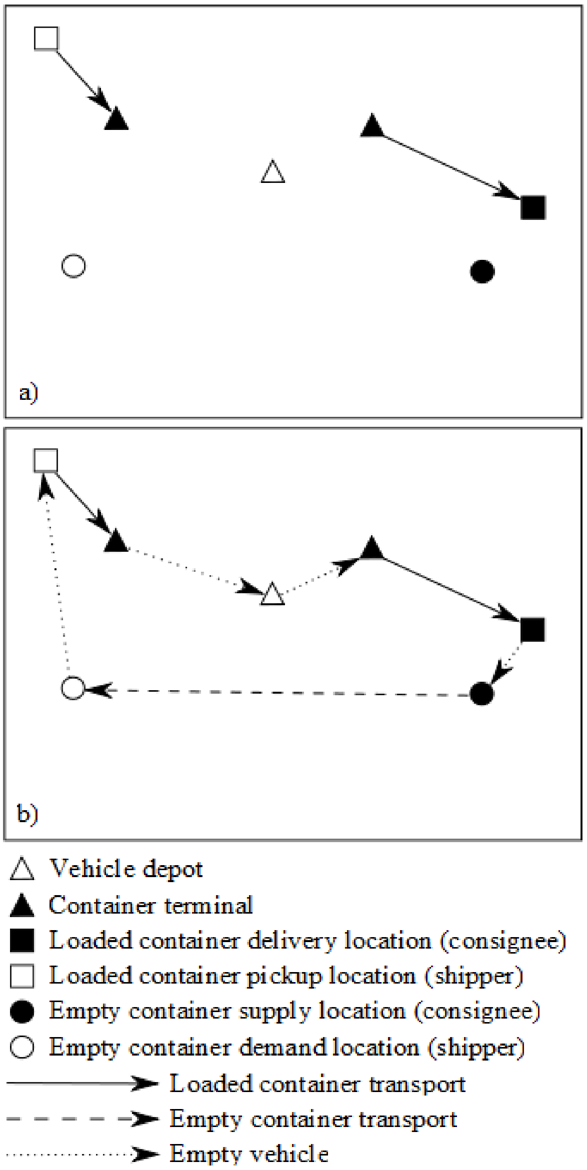

Figure 1: Small Problem Example with Solution

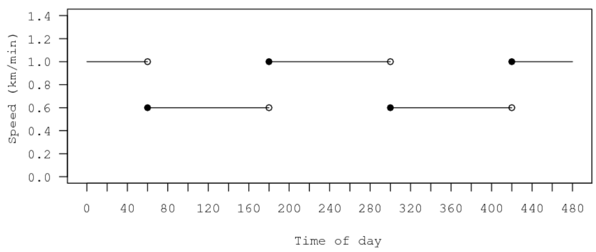

Figure 2: Speed Distribution

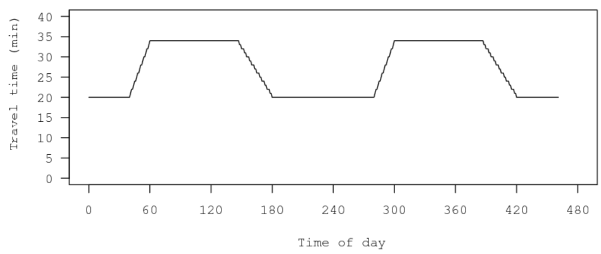

Figure 3: Travel Times on a Link of 20 Kilometres

4. PROBLEM FORMULATION

The problem described in the previous section may be formulated as an asymmetric multiple vehicle Travelling Salesman Problem with Time Windows (am-TSPTW) as is shown in Zhang, Yun, and Moon (2009) and Braekers, Caris, and, Janssens (2012). The problem is defined on a graph $G = (N, A)$ with node set N and arc set A. The node set $N = \{0,1, \dots, n\}$ consists of a vehicle depot (N_{VD}, index 0), a set of nodes for the loaded container transport tasks (N_L), a set of nodes for the empty container demand locations (N_D) and a set of nodes for the empty container supply locations (N_S). Each node has a time window $[a_i, b_i]$ during which it should be visited. The vehicle depot (as well as the container terminals) are opened during the whole planning period $[0, P]$.

When travelling between certain types of nodes, an intermediate stop at a container terminal is required. This is the case when travelling:

- from an empty container supply node to the vehicle depot, a loaded container task or another supply node,
- from the vehicle depot, a loaded container task or an empty container demand node to another container demand node.

In the first case, it is necessary to drop off the empty container which was picked up at the supply node before the vehicle is able to finish its route at the vehicle depot, transport a loaded container or pickup another empty container. The terminal which is used to drop off the empty container is chosen such that the duration of the detour is as small as possible. Similarly, when leaving the vehicle depot, finishing a loaded container task or dropping of an empty container at a demand node, an empty container needs to be picked up at a container terminal before travelling to an empty container demand node.

The arrival time function $A_{ij}(t)$ indicates the earliest arrival time at node j when a vehicle leaves node i at time t. The time needed to arrive at node j when leaving node i at time t is equal to $A_{ij}(t) - t$ and includes the execution of the loaded transport task at node i (if $i \in N_L$), the time to travel from node i to node j including a possible detour to a container terminal, container pickup and drop off times and possible waiting times at node j.

Travel times between two locations are calculated using the method of Ichoua, Gendreau, and Potvin (2003) which ensures that the non-passing property is satisfied. As a consequence, the arrival time function is a monotonic increasing function. Hence the inverse of the function $A_{ij}^{-1}(t)$ exists as well. This inverse function indicates the latest arrival time at node i in order to arrive at node j at the latest at time t. The values of $A_{ij}^{-1}(t)$ are calculated in a similar way as those of $A_{ij}(t)$. The major advantage of the existence of the inverse function is that it is possible to calculate backwards in a route. Hence, route feasibility checks may be formed in constant time (Ahn and Shin 1991; Fleischmann, Gietz, and Gnutzmann 2004; Donati et al 2008).

The arc set in the network is composed of all links (i, j) which are feasible: $A = \{i, j \in N, i \neq j, A_{ij}(a_i) \leq b_j\}$. The set of vehicles is indicated by K (index k) while M represents a very large number. Two types of variables are considered: binary variables x_{ij}^k which indicate whether a vehicle k travels directly from node i to node j, and variables t_i^k which indicate the arrival time of vehicle k at node i. The problem is formulated as follows:

$$\text{lexmin} \begin{pmatrix} \sum_{k \in K} \sum_{i \in N} x_{0i}^k , \\ \sum_{k \in K} \left(\sum_{i \in N} x_{i0}^k A_{i0}(t_i^k) - t_0^k \right) \end{pmatrix} \tag{1}$$

Subject to:

$$\sum_{k \in K} \sum_{j \in N} x_{ij}^k = 1 \qquad \forall i \in N \backslash \{0\} \tag{2}$$

$$\sum_{k \in K} \sum_{j \in N} x_{0j}^k \leq |K| \tag{3}$$

$$\sum_{j \in N} x_{ij}^k = \sum_{j \in N} x_{ji}^k \qquad \forall i \in N, \forall k \in K \tag{4}$$

$$A_{ij}(t_i^k) \leq t_j^k + (1 - x_{ij}^k) M \qquad \forall (i, j) \in A, j \neq 0, \ \forall k \in K \tag{5}$$

$$A_{i0}(t_i^k) \leq P + (1 - x_{i0}^k) M \qquad \forall i \in N, \forall k \in K \tag{6}$$

$$a_i \leq t_i^k \leq b_i \qquad \forall i \in N, \forall k \in K \tag{7}$$

$$t_i^k \geq 0 \qquad \forall i \in N, \forall k \in K \tag{8}$$

$$x_{ij}^k \in \{0,1\} \qquad \forall (i, j) \in A, \forall k \in K \tag{9}$$

A hierarchical or lexicographic objective function is used (1). The primary objective is to minimize the number of vehicles used while the secondary objective is to minimize total route duration. Constraints (2), (3) and (4) are flow constraints. Constraint (5) ensures that a vehicle cannot arrive at a node before leaving the previous node and travelling to the new one. Constraint (6) ensures that all vehicles return to the vehicle depot before the end of the planning period. Time windows are represented by constraint (7). Finally, constraints (8) and (9) determine the domains of the decision variables.

5. TIME-DEPENDENT ALGORITHM

In this section, a two-phase deterministic annealing algorithm is presented for the integrated time-dependent drayage problem. Only a brief discussion of the general structure of this algorithm is presented here since it is similar to the algorithm discussed in Braekers, Caris, and Janssens (2012) for the time-independent integrated problem.

The algorithm starts with an initial solution which is constructed using a simple parallel insertion heuristic.

In the first phase of the algorithm, the number of vehicles is minimized while partially ignoring the secondary objective of minimizing total route duration. During the second phase of the algorithm, total route duration is minimized while the number of vehicles is kept fixed at its minimal value obtained in phase one.

During both phases, a deterministic annealing meta-heuristic is implemented to guide the search. Deterministic annealing is a meta-heuristic based on local search. During each iteration, neighbours of the current solution are found by local search operators. A neighbour is accepted to become the new current solution when it is better than the current solution or when the worsening in the objective value is smaller than a deterministic threshold value T. This deterministic threshold value is gradually lowered during the search. (Dueck and Scheuer 1990)

Details on the implementation of the local search operators and the calculation of the optimal departure time of vehicles at the depot are presented in the following paragraphs. Two approaches to reduce computation times of the algorithm are discussed as well.

5.1. Optimal Departure Time

In the time-independent case, the departure time of a vehicle which minimizes the duration of a route is equal to the latest possible departure time. By leaving the depot as late as possible, waiting times at customers are avoided as much as possible. Unfortunately, this is no longer true when travel times are time-dependent. Leaving the depot earlier than the latest possible time, might result in a route of shorter duration.

In this paper, the optimal departure time of a vehicle at the depot t_0^k is determined as follows. First, an interval in which t_0^k lies is determined. The upper bound of this interval is the latest departure time which satisfies time window constraints. The lower bound is equal to the departure time which corresponds with the earliest possible return time at the depot. This value can be found by a single backward loop through the route. Leaving the depot earlier than this value would result in waiting times along the route and hence in longer route durations. Second, for each departure time in the interval, the corresponding route duration is calculated by a forward loop through the route. Finally, the departure time which results in the smallest tour duration is selected.

5.2. Local Search Operators

Six different local search operators are implemented (Braekers, Caris, and Janssens 2012). Feasibility of local search moves may be checked in constant time, like in the time-independent case (see Section 4). However, evaluating the effect of a local search move on total route duration is much more complex when travel times are time-dependent. A shift in the arrival time at a node does not only affect arrival and waiting times at other nodes in the route. It may affect the travel time between any pair of consecutive nodes in the route as well. As a result, it is not possible to predict the effect of a local search move on total route duration (Fleischmann, Gietz, and Gnutzmann 2004).

The local search operators which only affect the total duration of a solution (*intra-route, relocate, 2-Opt*, exchange*) are implemented as follows. Each time a feasible local search move is found, the move is carried out, optimal departure times of the vehicle are recalculated and the effect on route duration is found. When this effect is acceptable (lower than the threshold), the neighbouring solution is accepted. Otherwise the local search move is reversed and the search of the operator is continued.

The two operators that reduce the number of routes are implemented in a different way. These operators are involved with re-inserting multiple nodes during a single local search move. Often multiple feasible insertion positions for each node can be found. Evaluating the effect on total route duration for all feasible positions would take too much computation time. Therefore, the effect on total route duration is estimated by looking at the effect on total minimal duration, where total minimal duration is defined as the sum of the smallest possible travel times on each link in the solution. This effect can be calculated in constant time. Selecting the insertion positions in this way offers the advantage that the optimal departure times of the vehicles at the depot and the corresponding total route duration do not have to be updated after every insertion. Instead they are updated when all nodes are inserted and only when the operator succeeds in reducing the number of vehicles.

5.3. Speed-up Approaches

To reduce the computation time of the algorithm, two speed-up approaches are considered. These approaches are compared with the base algorithm (v0) in the Section 6.

The first approach (v1) is to calculate the optimal departure time of a vehicle only in a post-optimization phase, rather than recalculating it every time a local search move changes the route. Dabia, Ropke, and Van Woensel (2011) note that this is a common approach, both in literature and practice. During the search, the latest possible departure time at the depot is assumed to be the optimal one. To reduce the risk of ignoring potentially promising solutions, the fifty best solutions are stored during the search instead of just the single best solution. In a post-optimization phase, the optimal departure times are calculated for each of these fifty solutions and the solution which offers the lowest total route duration is reported.

The second speed-up approach (v2) is related to reducing the number of feasible local search moves which are carried out and subsequently need to be reversed. This occurs when the increase in total route duration is larger than the deterministic threshold value T. It is proposed to only carry out a selection of the feasible local search moves while rejecting other moves immediately. This selection is based on the effect of a local search move on total minimal duration. Moves which result in an increase in total minimal duration which is larger than the current threshold values T plus its maximum value T_{max}, are rejected immediately. The idea is that a move which results in a considerable increase in total minimal duration will probably not result in an acceptable effect on total route duration. Finally, a combination of both speed-up approaches (v3) is considered.

6. EXPERIMENTAL RESULTS

The proposed deterministic annealing algorithm is tested on a set of randomly generated problem instances. A 2^4 full factorial design is set up to ensure the robustness of the algorithm. For each of the 16 problem classes, 3 random problem instances are generated. Lower bounds on the number of vehicles and on total route duration are found by a time window partitioning method. For a detailed description of the factorial design and the calculation of the lower bounds, the reader is referred to Braekers, Caris, and Janssens (2012).

Table 1 gives an overview of the average results over fifty runs of the algorithm. Detailed results for the base algorithm (v0) are available in appendix. It is clear that the algorithm provides high quality results. Using one of the speed-up approaches (v1, v2), hardly affects solution quality while computation times are reduced by 20 to 25%. Even when a combination of both speed-up approaches is considered (v3), the negative effect on solution quality is limited while computation times are reduced by 30%.

Table 1: Overview of Results

Values	Average results			
	v0	v1	v2	v3
Vehicles used	11.16	11.17	11.17	11.17
Gap (absolute)	1.16	1.17	1.17	1.17
Duration	4751	4752	4751	4752
Gap (%)	3.40	3.41	3.40	3.43
Comp. time (s)	14.87	11.74	11.14	10.35

7. CONCLUSIONS

In this paper, it is studied how hourly variations in travel times due to congestion can be taken into account when planning drayage operations. An integrated planning approach is considered. The objective is to minimize first the number of vehicles and second total route duration. A deterministic annealing meta-heuristic is proposed to solve the problem. This algorithm provides high quality results. Finally, two approaches to speed-up the algorithm are proposed.

In the future, supplementary computational tests could be performed. It would be interesting to analyze the performance of the algorithm when not all links in the network have the same speed distribution. Furthermore, more complex speed distributions with multiple speed levels may be considered. Another interesting research direction would be to study a dynamic version of the problem where transportation tasks become known during the day and travel times are not necessarily known at the beginning of the planning period.

APPENDIX

Average results over fifty runs of the base algorithm (v0) are shown in Table A.1. The first two columns indicate the average number of vehicles used and the absolute gap with the lower bound. Columns three and four show the average total duration and the relative gap with the lower bound.

Table A1: Detailed Results

Instance	Results			
	V	ΔV	D	ΔD
1.1	7.00	0.00	2807	2.97
1.2	7.00	1.00	2921	1.46
1.3	7.00	1.00	2861	2.86
2.1	7.00	1.00	2871	1.44
2.2	6.00	0.00	2697	2.87
2.3	7.00	1.00	2739	2.21
3.1	6.00	0.00	2558	2.65
3.2	6.00	0.00	2626	2.69
3.3	7.00	1.00	2785	2.44
4.1	6.00	0.00	2534	2.14
4.2	6.00	1.00	2433	2.03
4.3	6.00	1.00	2416	1.78
5.1	12.66	1.66	5457	3.65
5.2	13.00	1.00	5548	2.35
5.3	13.00	1.00	5496	3.24
6.1	13.00	1.00	5602	4.30
6.2	12.00	1.00	5411	5.84
6.3	12.00	1.00	5407	4.98
7.1	11.04	0.04	4968	3.72
7.2	11.80	0.80	5076	2.47
7.3	11.44	0.44	5031	2.68
8.1	11.00	1.00	4830	4.64
8.2	11.00	1.00	4826	5.32
8.3	11.00	1.00	4780	5.85
9.1	10.00	1.00	4298	2.03
9.2	11.00	1.00	4642	0.98
9.3	10.00	0.00	4187	2.61
10.1	10.00	1.00	4281	1.70
10.2	9.00	1.00	3856	1.51
10.3	9.00	1.00	3869	2.70
11.1	9.00	1.00	3703	3.40
11.2	8.90	0.90	3527	2.68
11.3	9.00	1.00	3711	2.20
12.1	8.00	1.00	3413	3.14
12.2	8.00	1.00	3442	3.19
12.3	9.00	1.00	3699	2.21
13.1	19.00	3.00	7934	4.26
13.2	18.00	2.00	7733	2.93
13.3	18.80	2.80	7724	3.12

14.1	18.90	2.90	7932	5.65
14.2	18.00	2.00	7729	5.16
14.3	17.98	2.98	7526	5.46
15.1	15.64	1.64	6679	4.34
15.2	16.76	2.76	7016	4.06
15.3	15.94	1.94	6677	4.21
16.1	15.00	2.00	6453	6.65
16.2	15.00	1.00	6690	6.00
16.3	15.00	2.00	6639	6.23

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