Abstract

Vehicle routing and scheduling play a crucial role in the distribution chain. Although this research area has been broadly studied in the literature, there is still a lack of models closely representing real life problems. Most of the models proposed address constant travel times between nodes, without taking into account rush hours traffic congestion. In real applications in urban contexts the increasing of travel times due to congestion effects cannot be neglected. Models dealing with time dependent travel times work with simplified step functions, discretizing the time horizon in small time intervals. Even if this approach is broadly used, assuming travel times varying with discrete jumps is a strong approximation of real world conditions which evolve continuously. Another strong approximation adopted in the literature is that travel time (or speed) is computed on direct links, while in the real world vehicles travels on a road network, in which Euclidean distances do not hold anymore. In this paper, a vehicle routing problem (VRP) on a real road network with time dependent travel speed expressed by a polynomial function is addressed. Despite the difficulty to work with these kind of function, in this way congestion evolution behavior may be more precisely represented. In real situations, it is common to face different congestion peaks during the day, each one of which generally has different characteristics. Morning peaks are very sharp, i.e. congestion level rapidly increase reaching its maximum value which last for a short time after what congestion rapidly decrease, while evening peaks are generally much more spread across a longer time period and congestion variations are much more smoothed. Step functions, commonly used in practice, cannot represent at all realistic situations and peaks; linear functions may acceptable represents sharp peaks but not wider once. Polynomials, indeed, are able to better describe each type of peak. An application on Torino road network is presented. Speed evolution laws on main arcs are computed basing on real data obtained from an analysis carried out on averaged travel speed measured by an electronic system with 5 minutes intervals over two weeks. Small streets for which this data are not available are supposed to have a constant travel speed. Computational results show that taking advantage on the available information on different rush hour peaks intensity and spread on different arcs, it is possible to obtain better vehicle routing and scheduling plan.

Keywords: Time dependent travel speed; real road network; vehicle routing;
1. Introduction

The frenzy increase of life rhythm, within large urban centers, in the modern society yield to the necessity of reaching an high level of efficiency in freight distribution, in order to provide better services and to be more competitive. City logistics service providers are nowadays expected to offer more reliable and reasonably priced delivery services. The complexity of underlying supply chains and increasing customer requirements demand for advanced planning systems producing cost-efficient and customer-friendly delivery tours. In fact, in the modern society, customers have become more exigent, and their requirements in terms of delivery conditions have strongly increased. They require goods to be delivered as soon as possible or within specific time windows during the day, therefore time has assumed a crucial role in logistics operation decision making. Due to a growing amount of traffic in the last decades and a limited capacity of the road network, traffic congestion has become a daily phenomenon (Kok et al. 2012). Traffic congestion may have several causes. Some are predictable, such as the large amount of commuter traffic during daily peak hours, while others are less predictable, such road accidents or vehicle breakdown. While the second ones cannot be foreseen, the first ones systematically occur, and it has been proved that the greatest part of observed delays depends on them (Skabardonis et al. 2003); therefore, they should be taken into account during the freight distribution planning stage. This is not a trivial issue because congestion level does not evolve according to the same law on all the arcs belonging to the same urban area, and traffic peaks may be reached in different moments of the day for different arcs, and they may last for few minutes, as for longer periods. Today’s planning systems do not consider such time-dependent information; instead, they refer to rough travel time estimates in order to determine delivery tours while ignoring time-dependent variation of travel times. Thus, resulting delivery tours may be far from optimality, reliability and sometimes even far from feasibility. Inaccurate estimation of travel times may lead to higher routing costs, dissatisfaction of customers, driver overtimes, and penalties due to failing to meet customer time windows, with negative consequences on the quality of the service provided.

Another crucial issue concerns the network representation. Models presented in the literature generally work on networks composed by nodes and direct arcs connecting each couple of nodes. This representation does not hold for realistic problems, in which nodes are connected by path composed by part of different arcs, each one of which characterized by its own average speed and a variable congestion level during the day. Time-dependent travel time (or travel speed) models generally consider direct arcs and group them into few classes having the same congestion evolution function, (Ichoua et al. 2003). This is a strong simplification which does not allow to correctly represent real urban networks.

This paper deals with vehicle routing and scheduling on a real network with time dependent travel speed. The network is assumed to be composed by two kind of arcs. The first one represents main roads, which are affected by traffic congestion and characterized by a variable travel speed during the day. Each one of these arcs has its own travel speed variation law. The second kind of arcs represent small street not affected by congestion, for which we may assume constant travel speed. The network is connected, i.e. it is possible to reach each point of the network starting from every other point. The arcs are considered always one-way. For two-ways road two different arcs are generated, each one with its own characteristics. In fact, traffic congestion level can be sensibly different depending on the direction along which we travel it. For instance, during early morning hours, arcs entering the city centers are generally strongly congested, while traffic is fluid on the opposite direction, while the opposite behavior can be observed in late afternoon.

The goal of the paper is to show that taking into account time-dependent travel speed during the vehicle routing and scheduling phase, may yield to obtain better tours configurations with a consequent reduction of global travel times, and therefore, to be able to provide a better and cheaper service for the customers.

The paper is organized as follows. In Section 2, a deep and critical analysis of literature review on time-dependent vehicle routing is provided. In Section 3 a description of the problem analyzed is given, while the heuristic method, used to optimize the routing and scheduling of vehicles, is described in Section 4. An application on the real road network of Torino, in Italy, is showed in Section 5, where vehicle tours configuration provided considering time-dependent travel speed arcs are compared with the solution obtained considering static travel speed on arcs. Finally, Section 6 is devoted to conclusions and future developments.
2. Literature review

The routing and scheduling of a fleet of vehicles to service customers has been widely studied in the literature (Ball et al. (1995) and Toth and Vigo (2002)). However, there is still a lack of modeling approaches that more closely represent real-life conditions. One practical aspect that has been addressed rarely addressed is the time dependency of travel times on the time of the day. The largest part of available models assume that constant travel times or exploit simple procedures to adjust them, like multiplier factors associated with different periods of the day. Unfortunately, these assumptions cannot allow to give an accurate approximations of the real-world conditions where travel times are subject to more complex variations over time. Time-dependent vehicle routing problems are harder to model and to solve and have received a limited attention in the literature.

In Crainic et al. (2012), different scenarios, in each one of which travel time on arcs is different but it is supposed to be constant along all the delivery phase. This approach could be adopted to analyze different periods of the day, as early morning, lunch time, late afternoon, under the assumption that the delivery operations are performed within the same time period, that could hold in some practical application, or when only qualitative responses are needed, (i.e. How much do we gain performing delivery during the afternoon instead to carry out it in the early morning?) while it requires too strong approximation in problems in which more precision is requested or in which travel time fluctuations are very frequent.

In Malandraki and Daskin (1992) the authors examine the time-dependent vehicle routing problem (TDVRP). They provide mixed integer linear programming formulations including time windows, vehicle capacities and allow for waiting at customers location. Travel times are computed using simple step functions. A Nearest-neighbor based heuristic and a branch-and-cut algorithm for solving small problems (10–25 nodes) are proposed, while in Malandraki and Dial (1996), a dynamic programming algorithm is used to solve the time-dependent traveling salesman problem (TDTSP), which is a special case of the TDVRP in which a single vehicle is considered. Hill and Benton (1992) consider a time-dependent vehicle routing problem without time windows and propose a model based on time-dependent travel speeds. Computational results are reported only on a small example with a single vehicle and five locations. The major weakness of these models is that they do not satisfy the “first-in–first-out” (FIFO) property, i.e. using a step function it would happen that a vehicle \( i \) leaving node A after a vehicle \( j \) (having the same characteristics as \( i \)) will reach node B before \( j \). This fact makes step functions, clearly unadapt to realistically represent travel time (or speed) evolution in real applications. Continuous travel time functions seem to be more appropriate to model real-world conditions. In Ichoua et al. (2003), the authors presents a time-dependent travel speed model in which time is discretized into time-slots, that could be as small as necessary to correctly describe speed fluctuation, and travel speed is given by a different linear function for each slot, ensuring continuity on the border of the timeslots. In this way, travel speed is defined as a continuous function and could be better represent real cases. Nevertheless, this approach could not correctly represents peaks sharpness because travel speed is supposed to linearly vary. To avoid this inconvenient, and to have a more precise description of the reality, polynomial functions should be used.

3. Problem Definition

In this paper the Time-Dependent Vehicle Routing Problem with time windows and services time at nodes is considered. This problem is an extension of the classical VRP in which travel times vary over time and in which fixed service times at nodes are considered. Two large time windows are defined, holding for all the customers. These represents cases in which delivery may be performed during the morning or during the afternoon. This assumption fit well with shops or more generally, activities (factory, and so on..) which close at lunch time. No capacity limits are imposed on the vehicles, but each vehicle is supposed to perform its tour within the same time-windows he started it. The same vehicle may perform two different tours, one in the morning and one in the afternoon, but not more than one tour within the same period. Customers are connected among each other not by direct links, but by paths composed by parts of different road arcs, each one of which with its travel speed function varying on time. As stated above, there are two kind of arcs in the network: the first one represents main roads, which are affected by traffic congestion and characterized by a variable travel speed during the day. Each one of these arcs has its own travel speed variation law. The second kind of arcs represent small street not affected by
congestion, for which constant travel speed may be assumed. The goal of the problem is to minimize the total travel time on the network. Travel speed on arcs, is expressed by a polynomial function of time. With a unique function we describe speed behavior on the whole day, without the needing of discretizing the time space, automatically ensuring, consequently, continuity and differentiability of the function.

4. A GRASP heuristic for the TDVRP with time windows and services time at nodes

GRASP is a multi-start metaheuristic for combinatorial problems, in which each iteration consists basically of two phases: construction and local search, (Gendreau and Potvin, 2010) The construction phase builds a feasible solution, whose neighborhood is investigated until a local minimum is found during the local search phase. The best overall solution is kept as the result. (See Feo and Resende (1995), Festa and Resende (2009a) and Festa and Resende (2009b) for a detailed survey of the method and its applications). GRASP is called greedy because a solution is obtained following a construction heuristic which build up the solution step by step. Differently from classic greedy algorithms, decisions rule applied at each step are not deterministic but a random component is considered. Different alternatives are evaluated and a probability of being selected from the algorithm is generated basing on the quality of the alternative. Decisions made at each step, as in the deterministic case, do not necessary provide the best solution, because they are take, each time, following a myopic rule. Nevertheless, generally the quality obtained following this procedure is quite higher than what reached following a deterministic rule. Probabilities are adapted, at each step of the solution, basing on the previously made decisions. This procedure is inserted in a multi-start mechanism in order to create several solutions. Each solution is then improved by a Local Search algorithm.

The proposed GRASP for the TDVRP with time windows and services time at nodes works as follows:

1. First of all, the travel time, necessary to reach each customer at the beginning of the time-window, is computed in the following way: for each arc involved in the path, the speed according to which it is cover is supposed to be constant during the travel and it is taken equal to the value of the speed function calculated in the initial time in which we enter the arc. This procedure does not guarantee that the FIFO property is respected, but, being a polynomial function very smooth (at least much smoother than step or linear functions proposed in literature), and being travel times, within a urban context, generally small, the FIFO property violation becomes an extremely rare event.

2. A fitness function for each customer, is defined as the inverse of the sum of travel times necessary to cover each arc in the path, multiplied by a congestion coefficient of arc \( a \) at time \( t \) (time on which we enter the arc), \( C_{at} \). This coefficient is computed as:

\[
C_{at} = \frac{S_{at}}{S_{a0}}
\]

where \( S_{at} \) is the travel speed on arc \( a \) if entered at time \( t \), while \( S_{a0} \) is the speed at which the arc is traveled when traffic congestion is null. This adjustment allows to take into account, that if in a moment of the day, a path connecting to a customers is particularly free of congestion, it could be profitable to cover it in that moment even if that customer is not the nearest from the current position.

3. Probability are computed basing on the fitness function
4. A customer i is randomly selected following the probabilities computed on step 3
5. Customer i is inserted as next customer in the route; travel time and service at customer time are added at current time
6. Steps 2-5 are repeated until no further customers may be added to the route without violating time window
7. Steps 1-6 are repeated until there no more available vehicles for the considered delivery time window or until all the customers are served
8. If there are still customers unrouted repeat steps 1-7 for a new delivery time window

The above described procedure is iterated for a fixed number of iterations, \( N \), finding \( N \) potentially different solutions. At the end of the process each solution is post-optimized by a local search procedure, LS in which, at each iteration, a customer is exchanged with a customer within a prefixed radius \( R \). In this way, respect to a classical local search in which all the possible customers exchange are tested, the exploration of the neighborhood is faster, and only promising solution are taken into account. After that, a further optimization algorithm, named SHIFTING is applied, consisting in shifting each tour of small time intervals, in order to check if starting the tour later, would imply a reduction of global travel time. The procedure ends when the solution is no more feasible because the tour cannot be completed within the time window. The starting time yielding the smaller travel time is kept in the vehicle scheduling.

5. The case of Torino

Torino is an almost one million of habitants city located in North-West of Italy. In the last years traffic congestion has received a relevant attention in large urban center in Italy. Particularly, in Torino, there is a society operating in Intelligent Transport Systems and Infomobility, called 5T, (www.5t.torino.it/) which provide real time information on traffic congestion on the main streets of Torino. Although this information is useful for just-in-time delivery operation, or for private cars movements inside the city, it cannot be used in a planning phase, because of its extreme variability on time. For this reason 5T started to catalogue data on the whole day in order to provide a description of how congestion evolves, on each arc of the road network, during the day. They provide data, related to Torino main streets, with the current speed on arc, with 5 minutes time intervals. The amount of data is huge, and so a very precise information can be extracted from them. For small streets, for which this kind of data is not available, congestion is supposed to be null, and an average travel speed can be found by Google Maps (www.googlemaps.com).

The example proposed in this paper deals with ten visit points, each one of which identifies a block in which different customers may be grouped, located in strategic point of the city as hospital, railway station, factories and so on. For each visit point a fixed service time, depending on the number of customers included in the visit.

Visits may be performed within the following two time windows: 8:30-13:00 and 15:00-19:30. In Fig. 1 is reported a map of Torino, with underlined in blue arc for which congestion data are available (42), green circle representing visit points and a red circle representing the depot. Two tours, one in the morning an one in the afternoon must be scheduled.
As said in the previous sections, traffic congestion, and consequently travel speed sensibly vary during the day. Although similar behaviours may be observed for all the arcs (a congestion peak in the early morning, a smaller one during lunch time and another peak in the late afternoon), each arc presents peaks characterized by different sharpness, and rush hour may slightly vary among arcs. Therefore, each one-way arc travel speed is represented by a different travel speed function. These functions are sixth degree polynomials obtained fitting data points collected from 5T. Only data from 7:00 to 20:00 have been considered, with a 5 minute interval. The speed value at each time slot is obtained as an average value over two weeks (excluding saturday and sunday), in order to avoid that occasional traffic congestion given by accidents or special events to influence the speed evaluation. In Fig. 2 three different travel speed functions, on three different arcs, entering the city, are reported, while Fig. 3 shows how travel speed evolution can be different on the two ways of the same arc.

In the following graphics, readers find, on the Y axes, speed (expressed in Km/h) while on the X axes, time interval number (i.e. number 1 correspond to 7:00 in the morning, nume 2 to 7:05 and so on.).
Fig. 2. Travel speed function for Corso Orbassano, Corso Potenza and Corso Grosseto on the city entering direction

\[ y = 4E-10x^6 - 2E-07x^5 + 2E-05x^4 - 0.0017x^3 + 0.0582x^2 - 0.7789x + 20.214 \]

\[ y = 2E-10x^6 - 7E-08x^5 + 1E-05x^4 - 0.0011x^3 + 0.045x^2 - 0.7591x + 35.839 \]

\[ y = 1E-10x^6 - 5E-08x^5 + 7E-06x^4 - 0.0005x^3 + 0.0156x^2 - 0.2114x + 34.578 \]
Fig. 3. Travel speed function for Corso Trapani on city entering and exiting ways

For the arc considered in Figure 3, Corso Trapani, it could be noticed that on the exiting way, travel speed is almost constant between 10:00 and 15:00, which means that congestion level is quite small and stationary for a long period, while on the opposite way, speed decreases around 13:00 showing a relevant incoming traffic during lunchtime. Furthermore, speed variations are smaller on the entering way respecting to the exiting one. This behaviour can be explained considering that cars entrance in the city are more spread during the day, while exits are more concentrated in two small periods.

Computational tests have been carried out applying the GRASP+LS+SHIFTING on the Torino case. First, time-dependent travel speed are considered to compute selection probabilities during the construction phase. After that the algorithm has been ran again, but considering deterministic travel speed to compute the probabilities, and, after a complete solutions is built up, recalculating travel times considering time-dependent travel speed. The goal of this experiment is to show that taking into account foreseen congestion levels, i.e. considering variable speed on the arcs, it would be possible to obtain a better vehicle routing and scheduling respect to what obtained assuming speed to be constant for the whole day. 20 iterations of GRASP have been performed for each case (variable speed and constant speed) and a radius of 6 km has been applied in the LS phase, while intervals of 1 minute of shifting have been considered in the SHIFTING procedure. Average results, expressed in terms of traveled minutes, over 20 runs are reported in Tab. 1. As shown from the results, taking into account speed variations, it would be possible to save 12.5% of traveled minutes, with a consequent saving of money, both for driving costs and for cost of fuel consumed during unnecessary queuing. Furthermore, this approach is advantageous also from an environmental point of view, because it yield to a reduction of pollution emission given by the reduction of travel time on the network.
Table. 1. Results comparison between variable speed and constant speed approaches

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<tr>
<th>VARIABLE SPEED</th>
<th>CONSTANT SPEED</th>
<th>GAIN</th>
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<td>538.238</td>
<td>614.908</td>
<td>12.5%</td>
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6. Conclusions and Future Developments

This paper address the vehicle routing problem (VRP) with time windows and service time at nodes on a real road network with time dependent travel speed. Differently from previous works in literature, which uses simple step or linear function, the proposed approach consist of describing travel speed on arcs with polynomial functions, which are more adapted to represent real speed fluctuations. The main advantage of this approach is that it is not necessary to discretize the time space describing speed evolution with a different function in each time slot, (that could create continuity and/or differentiability problem), but speed can be described by a unique continuous and differentiable function over the whole time period. An application on Torino road network is presented. Speed evolution laws on main arcs are computed basing on real data obtained from an analysis carried out on averaged travel speed measured by an electronic system with 5 minutes intervals over two weeks. Small streets for which this data are not available are supposed to have a constant travel speed. A GRASP based heuristic is proposed to solve the problem. Computational results show that taking advantage on the available information on different rush hour peaks intensity and spread on different arcs, it is possible to obtain better vehicle routing and scheduling plan. Further developments could address the application of the proposed approach on larger size instances, or to more complex problems, as VRP with multiple time-windows, (different for each customer), pick-up and delivery problems, and to extensions of the classical VRP with heterogeneous fleet. The last cited problem, in particular, it could be of great interest for the scientific community, because it could be adapted to represent real cases in which there are limited traffic zones (LTZ) within the city center, which could be accessed only on restricted time periods by standard vehicles, or during the whole day by electric vehicles, which are very common situations in practice

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References