Solving the Open-Path Asymmetric Green Traveling Salesman Problem in a Realistic Urban Environment

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Abstract In this paper, a driving route planning system for multi-point routes is designed and developed. The routing problem has modeled as an Open-Path and Asymmetric Green Traveling Salesman Problem (OAG-TSP). The main objective of the proposed OAG-TSP is to find a route between a fixed origin and destination, visiting a group of intermediate points exactly once, minimizing the CO_2 emitted by the car and the total distance traveled. Thus, the developed transportation problem is a complex and multi-attribute variant of the well-known TSP. For its efficient solving, three classic meta-heuristics have been used: Simulated Annealing, Tabu Search and Variable Neighborhood Search. These approaches have been chosen for its easy adaptation and rapid execution times, something appreciated in this kind of real-world systems. The system developed has been built in a realistic simulation environment, using the open source framework Open Trip Planner. Additionally, three heterogeneous scenarios have been studied in three different cities of the Basque Country (Spain): Bilbao, Gazteiz and Donostia. Obtained results conclude that the most promising technique for solving this problem is the Simulated Annealing. The statistical significance of these findings is confirmed by the results of a Friedman's non-parametric test.

Key words: Route Planning, Traveling Salesman Problem, Emission reduction, Simulated Annealing, Tabu Search, Variable Neighborhood Search.

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1 Introduction

Route planning has gained a crucial importance in mobility management in last years. Traveling long and short distances daily has become a habit for many people world-wide. In this sense, two different route planning modes can be highlighted: multi-modal and mono-modal transportation. The first one aims at providing the traveler feasible routes between origin and destination using diverse public and private transportation modes. The second mode consists on routes performed by a single transport type. This second kind of routes are the focus of this study. More concretely, and as will be detailed later, routes performed by car, which are the most common ones for medium-length journeys. Furthermore, routes conducted by car are also the most usual ones for long-length paths, when the scheduling of public transportation is not the most suitable one. For these reasons, mono-modal transportation is widely referenced by the users. In this context, the most common mono-modal routes are the ones performed by car, bike or walking, developed for different purposes. Even for planning these kind of routes users take advantage of several route planners that are available in the market or in the web.

In recent years, multiple route planning systems available on the Internet have been developed for a wide range of transportation modes. Furthermore, most of these planners are open and freely available, popularizing their use in multiple contexts. These tools, accessible thought different platforms such as smartphones, tablets and computers, grant flexibility to the users for designing routes in any place and at any time. Furthermore, almost all these platforms for the building of paths composed by intermediate points, but not with the enough flexibility. Tools such as Google Maps[1] allow for the introduction of intermediate points, but they are visited in order of appearance, where not optimization is needed. In this sense, there are plenty of situations in which an optimized design of multi-point routes for this kind of platforms would be highly profitable for the end user. Some examples of these situation could be the transportation on demand [1] or the goods transportation. The lack of literature exploring this interesting novel aspect has motivated us to conduct the present study.

Concretely, the main contribution of this work is the development of a driving route planning system for multi-point routes, modeling the problem as an Open-Path Asymmetric Green Traveling Salesman Problem (OAG-TSP). The main objective of the developed algorithm—system—etc. is to find the optimal route between two different points, visiting a set of intermediate points exactly once, minimizing the distance traveled and the CO_2 emitted by the car. Furthermore, for the OAG-TSP solving three different classic meta-heuristics have been used: Simulated Annealing (SA, [2]), Tabu Search (TS, [3]) and Variable Neighborhood Search (VNS, [4]).

[1] https://www.google.es/maps/

The system developed in this study has been deployed in a realistic simulation environment, using the Open Trip Planner (OTP, [5]) open platform. In overall, three different real-world scenarios comprise the conducted experimentation. These scenarios have been placed in the three most important cities of the Basque Country (Spain): Gazteiz, Bilbao and Donostia. Additionally, three different configurations have been used for each scenario, resulting on an experimentation composed by nine separated tests. For these experiments, two different real data sources have been used: the Open Street Map of the whole Basque Country, and its Digital Elevation Model (DEM).

1.1 Background and Research Contribution

As can be deduced from its name, the proposed OAG-TSP is a complex variant of the well-known Traveling Salesman Problem (TSP, [6]). The TSP is one of the more studied benchmarking problems in artificial intelligence and operations research. The main reasons for its popularity and importance is its easy formulation and its complex resolution, which suppose a challenge for the scientific community. In this sense, the TSP is the focus of lots studies annually [7, 8]. Furthermore, the focus of the current scientific community is directed to the multi-attribute or rich variant of the TSP [9]. These kinds of problems are special cases of the well-known conventional TSP, with the distinction of having multiple constraints and complex formulations. These problems have a great scientific interest. While they maintain their complexity, their social interest is also high, as their applicability to real-world situations is greater than the conventional version. Recent examples of these multi-attribute routing problems can be found in [10], [11] or [12]. The OAG-TSP developed for this research can be placed in this category.

The originality of this paper rests on two different concepts: the first one is the application of a green multi-point route optimization algorithm into a car route planning open platform. This way, users can plan their driving paths using intermediate places and ordering them as an OAG-TSP. The other main originality is the modeling of the routing problem. This is the first work in the literature exploring the application of the well-known Vehicle Specific Power (VSP) concept into a vehicle routing problem, allowing in this way the reduction of pollutant gas emissions in TSP open path routes. Additionally, the application of such problem into a realistic environment supposes an added value for the conducted research [13]. This is so since it is infrequently done for TSP family problems, usually used as benchmarking problems.

The remaining of this work paper is structured as follows. In Section 2, the proposed OAG-TSP for facing the car route problem is described. In Section 3, the description of the deployed environment based on Open Trip Planner for facing the established requirements are described. Next, the experimentation performed is discussed in Section 4. Finally, this paper ends in Section 5 with conclusions and an outline of further research paths.

2 Problem Definition

As has been mentioned in the introduction, the routing problem addressed in this study has been modeled as an OAG-TSP problem. Considering this novel problem as a realistic variant of the TSP, it can be represented as a complete graph $\mathcal{G} \doteq (\mathcal{V}, \mathcal{A})$, where $\mathcal{V} \doteq \{v_1, v_2, \ldots, v_N\}$ denotes the group of nodes that represent the graph, which are the different points that the car should visit. On the other hand, $\mathcal{A} \doteq \{(v_i, v_j) : v_i, v_j \in \mathcal{V} \times \mathcal{V},\ i, j \in \{1, \ldots, N\} \times \{1, \ldots, N\}, i \neq j\}$ is the set of edges connecting every pair of nodes in $\mathcal{V}$, which represent the streets of the cities. Furthermore, each edge has an associated cost $d_{ij} \in \mathbb{R}^+$, related to the traveling costs thorough this arc. Additionally, due to the asymmetric characteristic of the problem, $d_{ij} \neq d_{ji}$ in most of the cases. The reason for this asymmetry is related to the difference in traffic flow in both directions. In addition to this weight characteristic, each edge has an emission value $em_{ij} \in \mathbb{R}^+$ associated, which is based on the well-known VSP [14] measure. This metric follows the same philosophy as d_{ij} in terms of asymmetry, and the mathematical procedure for calculating its value is described later, in Subsection 2.1.

With all this, the proposed OAG-TSP hinges on the discovery of a route that visits every node once and only once, starting and ending in two different defined nodes, and minimizing an objective function composed by the emission and the traveling costs. This optimization problem can be formally stated as

$$\text{minimize} \quad f(\mathbf{X}) = \sum_{i=1}^{N} \sum_{\substack{j=1 \\ i \neq j}}^{N} w_d(\psi_d(i,j)) + w_{em}(\psi_{em}(i,j)) \tag{1a}$$

$$\text{subject to} \quad \sum_{\substack{j=1 \\ i \neq j}}^{N} x_{ij} = 1, \quad \forall j \in \{1, \ldots, N\}, \tag{1b}$$

$$\sum_{\substack{i=1 \\ i \neq j}}^{N} x_{ij} = 1, \quad \forall i \in \{1, \ldots, N\}, \tag{1c}$$

$$\sum_{\substack{i \in \mathcal{S} \\ j \in \mathcal{S} \\ i \neq j}} x_{ij} \geq 1, \quad \forall \mathcal{S} \subset \mathcal{V},, \tag{1d}$$

$$w_d + w_{em} = 1,\ 0 < w_d, w_{em} < 1 \tag{1e}$$

where $\mathbf{X} \doteq [x_{ij}]$ is a $N \times N$ binary matrix whose entry $x_{ij} \in \{0, 1\}$ takes value 1 if edge (i, j) is used in the solution. With all this notation in mind, the objective function represented in Expression (1a) is the sum of costs and emissions associated to all the arcs contained in the solution. Additionally, each of these separated values are weighted using two parameters w_d and w_{em}. clauses (1b) and (1c) guarantee that each node is visited only once. Finally, (1d) ensures the absence of sub-tours, and forces that any subset of nodes S has to be abandoned at least one time. This constraint is crucial for avoiding cycles along the route.

2.1 Quantifying CO_2 Emission

As has been pointed before, the VSP formula has been used as base for the CO_2 emission calculation. This concept is a formalism used in the evaluation of vehicle emission, and it was first developed by J. L. Jimenez in 1998 [15] at the Massachusetts Institute of Technology.

Briefly explained, the VSP is the summation of the load resulting from acceleration, hill climbing, rolling resistance and aerodynamic drag, all of them divided by the mass of the corresponding vehicle. This measure is usually represented in kilowatts per tonne, and it depicts the instantaneous power demanded by the vehicle divided by its mass. In general terms, this formula can be used to calculate the vehicle CO_2 emissions whether it is combined with remote-sensing and dynamometer measurements.

In the early 2000s, the United States Environmental Protection Agency (EPA) adopted the VSP to calculate of vehicle pollutant gas emissions. As can be read in the technical report published by the EPA in [16], the concept of VSP has been considered in a wide variety of research and applied studies in different ways, showing its potential and usefulness as metric for characterizing vehicle emissions. With the aim of facilitating this calculation, a generalization of the formula was developed for light duty vehicles:

$$VSP = v[1.1a + 9.81(\text{atan}(\sin(grade))) + 0.132] + 0.000302v^3, \qquad (2)$$

where VSP is given in $kW/Metric\ Ton$, v in m/s, a in m/s^2, and grade is the road slope measured in percentage (%). In any case, as can be read in [16] the VSP cannot be directly applied for calculating reliable emissions. For this reason, the North Carolina State University (NCSU) proposed a *binning* approach in which operational bins were defined based on speed, acceleration, and power demand, and estimates within each modal bin were refined using ordinary least squares (OLS) regression analysis [17]. In this sense, the Table 1 is used for calculating the resultant VSP mode based on a VSP value. Furthermore, once the VSP is established in a specific VSP Mode, the corresponding emitted CO_2 grams per second can be deduced using the column represented as $em_{i,j}$ in the same table. In this sense, for every second a light vehicle spends in a street, the CO_2 value related to its VSP Mode is added. Finally, as will be mentioned later, the Digital Elevation Model has been used for calculating the elevation and the grades of each street of the cities.

Table 1 VSP Bin Definitions Developed by NCSU.

VSP Mode	VSP [kW/Metric Ton]	$em_{i,j}$	VSP Mode	VSP [kW/Metric Ton]	$em_{i,j}$
1	VSP <-2	2.25	8	13 ≤ VSP <16	6.50
2	-2 ≤ VSP <0	2.00	9	16 ≤ VSP <19	7.00
3	0 ≤ VSP <1	1.50	10	19 ≤ VSP <23	7.25
4	1 ≤ VSP <4	3.50	11	23 ≤ VSP <28	8.00
5	4 ≤ VSP <7	4.75	12	28 ≤ VSP <33	9.00
6	7 ≤ VSP <10	5.50	13	33 ≤ VSP <39	9.50
7	10 ≤ VSP <13	6.00	14	39 ≤ VSP	10.0

Summarizing, the $\psi_{em}(i,j)$ associated to each street is calculated using the following formula: $\psi_{em}(i,j) = seconds\_in\_street * em_{i,j}$. In other words, for calculating the CO_2 emitted by a car traversing a street, the seconds that the vehicle needs to go through this street is multiplied by the associated VSP.

3 Description of the Simulation Environment

As has been highlighted along this paper, the developed routing system has been deployed using OTP. Briefly explained, OTP is an open source framework for mono and multi-modal journey planning. It is based on the client-server model, providing a map-based web interface, which has been used for the tests carried out during this research. Furthermore, OTP provides a REST API service for third-party applications, and it gives the opportunity of working with different open data standards. These are the main advantages that have encourage us for using this framework:

- It is open source, which facilitates its modification and adaptation to the proposed scenarios.
- It efficiently works with OSM and GeoTIFF, providing the structure to automatically build the street network and its elevations. As it is described in the following Section 4, these two standards are the ones used for this work.
- It is well documented, and it has an active community working behind. This fact facilitates the understanding of the framework.

For this research, the last version developed for the OTP has been used, which has been written in JAVA programming language. Additionally, the one written in JAVA programming language has been used. For this reason, all the modifications done for the correct adaptation of our conditions have been conducted using this language. The basic version of the OTP is not able to fulfill all the characteristics of the proposed study requisites, for this reason, both the source code and the client have been modified to meet the main objectives.

Because they fall outside the scope of this paper, the implementation details are not described in this paper. In any case, the main modification carried out is the adding of the meta-heuristic algorithms for solving the proposed OAG-TSP. Specifically, the local search algorithms that have been used are the SA, TS and VNS. We have chosen these three methods for the experimentation for various reasons. First of all, all these algorithms are well-known in the literature, and they have shown their efficiency for solving this kind of problem in multiple times [18, 19]. Furthermore, they are easy to implement and to adapt to the proposed problem, and they do not need a high computational effort for their running. This last reason has been the most important one. This is so since the route building by the OTP is a complex process requiring lots of calculations, leading to high execution times in case we use complex meta-heuristics. Some further modifications on the OTP code are related with the addition of the VSP calculation, and the consideration of intermediate point for the route calculation.

4 Experiments and Results

In this section, the experimentation carried out in this research is described. In overall, three different scenarios have been considered. These scenarios correspond to the three most important cities of the Basque Country (Spain): San Sebastian, Vitoria-Gazteiz and Bilbao. Each of these cities are recognized by different characteristics in terms of geographic profile and street distribution, making this experimentation heterogeneous enough to be representative. Furthermore, each instance has been generated using a fixed origin and destination, and 18 randomly chosen intermediate points.

For conducting the experimentation correctly, two open data sources have been used on the deployed platform:

- *Digital Elevation Model*: This data source is used with the intention of setting the elevations of the streets of the whole Basque Country. OTP uses these information for assigning the corresponding elevation to the entire street network, and it is employed for calculating the CO_2 emission of each route. Furthermore, this source is directly used by OTP in GeoTIFF format, and it has been openly taken from *SRTM Tile Grabber*[2] database.
- *OSM map file*:In order to build the complete street network for properly building the routes, the corresponding map file is needed. This file has been openly obtained from *Planet OSM* platform[3], using *BBBike*[4]. Through

[2] http://dwtkns.com/srtm/

[3] http://planet.osm.org

[4] http://download.bbbike.org/osm

this open tool, OSM maps have been downloaded in Protocolbuffer Binary Format (PBF), containing all the nodes, ways and relations necessary to build the map. These OSM files are directly consumed by OTP, which automatically constructs the full road network.

Additionally, it is interesting to mention that all the tests conducted in this work have been run on an Intel Core i7-7600 computer, with 2.90 GHz and a RAM of 16 GB. Furthermore, each scenario and configuration has been run 10 times for each algorithm. It is interesting to point that three different configurations have been tested for each scenario:

- Green alternative (G-Alt): In this case, the minimization of the CO_2 issued by the car has been prioritized. For this reason, the objective function used has been the following one: $w_d = 0.2$, $w_{em} = 0.8$.
- Short alternative (S-Alt): For this alternative, the minimization of the length of the route is prioritized over the emission, using the following objective function: $w_d = 0.8$, $w_{em} = 0.2$.
- Balanced alternative (B-Alt): For this last case, both objectives are considered using the same weights: $w_d = 0.5$, $w_{em} = 0.5$.

Regarding the parameterization of the algorithms, and following the good practices listed in [20], we have used the same functions and configuration for all the three cases with the aim of performing a fair comparison. The initial solutions of the used SA, TS and VNS are generated randomly, maintaining the position of the first and last node along the whole execution, and corresponding to the origin and the destination inserted by the user. Regarding the ending criterion, a maximum number of 200 iterations has been set after an empirical performance analysis. In this sense, it should be mentioned again that the calculation of a route by the OTP is a demanding process. For this reason, the maximum number of iterations should not be high, avoiding the increasing of the algorithm runtime. In relation to the successor functions used, TS and SA used the well-known swapping operator, while the VNS uses also the insertion function [21]. Furthermore, the initial temperature of SA has been set in 0.95, and the cooling factor in 0.01. On the other hand, the size of tabu list of the TS has been established in $problem\_size \times 2$, where $problem\_size$ is the number of nodes in the scenario. Table 2 summarizes the parameterization for each meta-heuristic.

Table 2 Parametrization of all developed methods.

SA		TS		VNS	
Parameter	Value	Parameter	Value	Parameter	Value
# evaluations	200	N. of evaluations	200	N. of evaluations	200
Successor Function	Swapping	Successor function	Swapping	Successor function	Insertion & Swapping
Cooling factor	0.01	Size of tabu list	$problem\_size \times 2$	Probability of choosing each function	0.5
Temperature	0.95	Memory type	Short Term [3]		

In the following Table 3, the results obtained by the SA, TS and VNS are show for each scenario and configuration. As can be observed on this table, SA is the algorithm that has reached the best results. Specifically, SA has obtained best outcomes in 7 out of 9 of the cases. Besides that, and following the guidelines in [22], one statistical test has been carried out to resolve the statistical relevance of the results. Thus, the Friedman's non-parametric test for multiple comparison allows proving if there are significant differences in the results obtained by all reported methods. This way, in the last row of Table 3, we have displayed the mean ranking returned by this nonparametric test for each of the compared algorithms and scenarios (the lower the rank, the better the performance). Additionally, the Friedman statistic obtained is 8.667. The confidence interval has been set in 99%, being 5.991 the critical point in a χ^2 distribution with 2 degrees of freedom. Since $8.667 > 5.991$, it can be concluded that there are significant differences among the results.

Table 3 Results obtained by the SA, TS and VNS for each scenario and configuration, and average rankings returned by the Friedman's non-parametric test.

	GASTEIZ		
	SA	TS	VNS
G-Alt	64281.7±3504.9	66914.5±4343.6	**63749.5**±4930.3
S-Alt	**59150.3**±5728.3	63315.4±3887.8	61157.7±5826.9
B-Alt	**58471.6**±4556.8	62381.6±4188.5	61644.5±4248.2
	BILBAO		
	SA	TS	VNS
G-Alt	**45862.0**±3144.7	48466.8±4963.9	48869.2±3500.1
S-Alt	**46346.6**±4841.8	49594.5±3536.0	51318.5±4095.2
B-Alt	**45155.9**±2576.5	48443.5±3351.9	49684.1±2814.6
	DONOSTI		
G-Alt	**35244.9**±3431.5	38142.1±2550.4	37291.8±2739.4
S-Alt	34969.6±2648.6	37673.5±2807.6	**34207.6**±1886.3
B-Alt	**33103.1**±1263.1	36911.6±2229.8	37313.2±2948.6
	Friedman's non-parametric test		
Rank	**1.4444**	1.7778	2.7778

Additionally, and in order to graphically show the best results obtained by each technique, the best green routes obtained for each considered scenario are depicted in Figure 1. Being specific, the first route corresponds to Gazteiz, and it has been obtained by the VNS. The second of the maps shows the best route found in Bilbao, reached by the SA. Finally, the third path correspond to Donostia, and it has been got also by the SA.

5 Conclusions and Further Work

In this work, a driving route planning system for multi-point routes is designed and developed, modeling the transportation problem as an Open-Path and Asymmetric Green Traveling Salesman Problem. The main goal of the OAG-TSP is to find a promising route between two different points, visiting a set of intermediate points exactly once, minimizing the CO_2 emitted by the driver and the distance traveled. In this sense, the developed problem is a complex and multi-attribute variant of the well-known TSP. For the OAG-TSP solving three different methods have been used: the SA, the TS and the VNS, which have been chosen for its easy adaptation and rapid

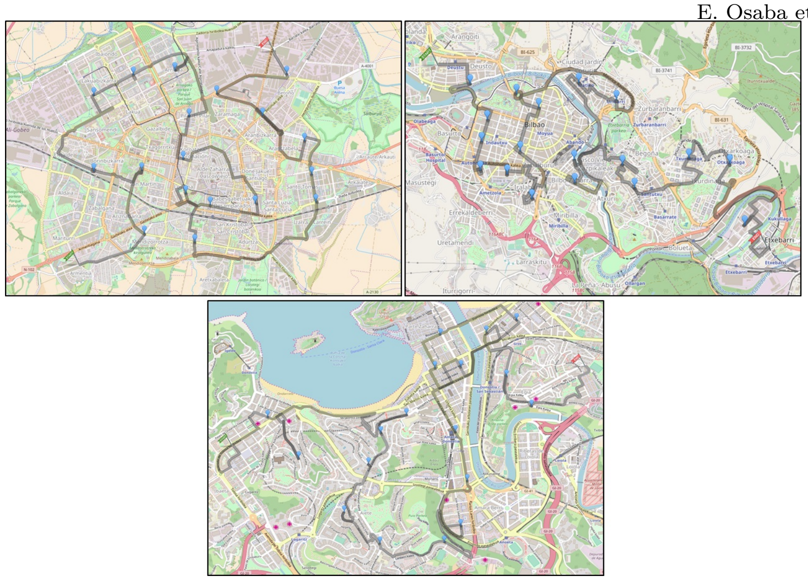

Fig. 1 Best routes found for each scenario. Top left: Gazteiz. Top right: Bilbao. Bottom: Donostia.

execution times. The system developed has been built in a realistic simulation environment, using the OTP. Furthermore, three different scenarios have been studied in three different cities of the Basque Country (Spain): Bilbao, Gazteiz and Donostia.

Several future work lines have been planned for the short term. The first one is the development of further tests in different cities of Spain, using more algorithms. Furthermore, additional research will be done regarding the transportation problem, applying further realistic restrictions and conditions.

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