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Hotel Selection in the Orienteering Problem with a Penalty for CO_2 Emission

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Abstract

This paper proposes the extension of a penalty for the emission of CO_2 to the orienteering problem with hotel selection. This thesis extends the problem by including a decision variable for modes of transport and examining the environmental effects of different transportation options. The main research question focuses on the effect of implementing a penalty for CO2 emissions in the model and emissions of various transportation modes are investigated to find the cost per kilometer of these emissions. It adjusts the existing model to include these emission costs. The results show that the inclusion of emission costs influences the choice of transportation modes and affects the objective values. The findings suggest that implementing a CO2 tax can be used as an incentive for the use of modes with lower emissions and decrease overall CO2 emissions. The paper concludes that passing on external costs to consumers through a CO2 tax is an effective approach to reduce emissions in the orienteering problem with hotel selection.

1 Introduction

While the orienteering problem is well-known, and has been studied for decades (Gunawan, Lau & Vansteenwegen, 2016), the hotel selection adds a whole new dimension to this problem (A. Divsalar, Vansteenwegen & Cattrysse, 2013). In the orienteering problem, the goal is to get the highest score possible by visiting vertices. Not all vertices can be visited. The hotel selection splits a large tour into multiple trips, where every day one trip takes place. The trip will start and end in a hotel.

This thesis discusses the problem statement of A. Divsalar et al. (2013), and their variable neighborhood search method. Moreover, it will add a new element to the orienteering problem with hotel selection, as a decision variable for modes of transport will be included in the model. This thesis will focus on the effects on the environment of different types of transport and will determine the costs per kilometer based on these external effects.

The main research question of this thesis is:

> What is the effect of implementing a penalty in the model of Divsalar et al. (2013) to account for the CO_2 emission of the transportation used in the orienteering problem with hotel selection?

The orienteering problem with hotel selection aims to maximize the obtained score, and therefore to travel through the nodes efficiently. By including the penalty for emissions, a trade-off between objectives is created: maximizing the obtained score and at the same time minimizing the costs. This challenging trade-off requires an adjustment to the model of A. Divsalar et al. (2013). And, in addition, educated estimations on the emissions of different modes of transportation and the costs of these emissions.

When regarding the Euclidean distances in kilometers, an application in tourism is very fitting. One could see the tour as a vacation, where a trip is made every day. By taking a car, it is possible to see more tourist attractions and highlights when travelling from hotel to hotel, but going by bike would be better for the environment and may add to the experience. Some trips may even be done on foot. Travel agencies may use this application when planning vacations for their customers. The set of transportation modes is selected for this application, but note that when this research is replicated with different types of transportation modes, it can have many more different applications. For instance, a logistic transport company could define a set of different types of trucks and vans that use different energy sources to optimize what vehicles should drive what trips when the time limit is too small to visit all customers. A faster vehicle may result in more visited customers and a higher profit, but there is a trade-off between maximizing the profit and minimizing the negative external effects. An electric vehicle will have much less external costs, but will need more time to charge than a diesel truck will need to fill up the tank. The aim of this paper is to allow companies to not only see the increase in profit when using a faster mode of transportation, but also see the CO_2 emission as a cost.

Other applications include surveillance and firefighting missions, where not only the trips but the optimal location of the stations are of great importance (Vathis, Konstantopoulos, Pantziou & Gavalas, 2023). Here the vehicles used have an effect on the route that can be travelled, and depending on the profit of the trip, the choice of vehicle influences the cost. Saving lives will lead to a high profit and will allow for using expensive vehicles, where saving a cat from a tree, for example, may not yield comparable profit and could lead to a preference of less expensive modes for transportation.

First I will discuss existing research on this topic and compare it to this problem in Section 2. The problem is explained in more detail in Section 3. The methodology of this model is discussed in Section 4, after which the results will be discussed in Section 5. This paper will close with a conclusion and discussion, in Section 6 and Section 7 respectively.

2 Literature Review

Since the publication of A. Divsalar et al. (2013) in 2013, many variations on the orienteering problem with hotel selection (OPHS) have been investigated. Personalizing the OPHS is an extension to this problem that has been seen more often in recent years. Tourism is adapting to the demand of more personal itineraries, and more global tourism. One example is the Cruise Itinerary Problem, where a cruise ship travels by multiple stopping points before returning home. Here the goal is visiting the best locations along the route. This is different than the Bus Touring Problem, where the focus lies on the arcs on the route, not the vertices visited (Ruiz-Meza & Montoya-Torres, 2022).

Other papers have layed more focus on the selection of hotels, ranking them with scores. To maximize the score of the visited vertices and at the same time optimizing the selection of hotels, Ataei, Divsalar and Saberi (2022) have created a multi-objective formulation of the OPHS.

Garcia, Linaza, Arbelaitz and Vansteenwegen (2009) have investigated adding the factor of transportation methods to the orienteering problem, without the hotel selection. They create routes using heuristics, while taking into account traffic and rush-hours as well.

The model presented in this paper is based on the OPHS presented by A. Divsalar et al. (2013). In the OPHS, there is a set of vertices and hotels. Every vertex has a score that is collected when the vertex is visited. Due to a time limitation on the tour, not all vertices can be visited and a selection has to be made. The optimal selection maximizes the obtained score. The hotel selection splits one large tour into multiple different trips. Both the total tour and the daily trips have a time limit. Only the starting and ending hotel are set, everything in between is not. A trip should start in the hotel the previous trip ended in and end in a hotel as well , these can be the same. A vertex can only be visited once in a tour. The tour of an OPHS is not necessarily a circuit, but it can easily be made into one by connecting the first and last hotel with a dummy arc or by setting the starting and ending hotel equal to each other (Vansteenwegen, Souffriau & Oudheusden, 2011).

A. Divsalar et al. (2013) approach this problem with a skewed variable neighborhood search (SVNS), which consists of three phases. First the solution is initialised using a greedy heuristic, followed by the shaking phase, where the vertices and hotels are 'shaken up' and the solution is improved using local search. Finally, the solution that will serve as the initial solution for the next step is chosen in the re-centering phase.

A. Divsalar, Vansteenwegen, Sörensen and Cattrysse (2014) have also published a memetic algorithm (MA) a year after publishing the SVNS. This algorithm shifts the focus from improving the vertices in between the hotels to improving the sequence of hotels itself. Another approach is a hyper-heuristic, introduced by Toledo, Riff and Neveu (2020). This approach can be seen as a large neighborhood search and uses both methods from the SVNS and the MA. Sohrabi, Ziarati and Keshtkaran (2020) have proposed an algorithm that does not use the potential score between hotels, but instead is based on dynamic programming. This algorithm applies a greedy randomized adaptive search procedure, and is therefore named GRASP (Sohrabi, Ziarati & Keshtkaran, 2021).

When the penalty for CO_2 emission is introduced, many aspects will remain similar to the original OPHS. The goal will remain the same, but a share of the score will be deducted as penalty. Moreover, an additional choice has to be made about the mode of transportation. This will affect both the penalty and the travelling speed. In general, faster modes of transportation have a higher penalty, but also yield a higher score. The point of interest is then to investigate this trade-off between better scores and higher costs.

A similar problem has been investigated by G. Divsalar, Divsalar, Jabbarzadeh and Sahebi (2022), where a multi-objective formulation is presented to design a trip that maximizes the score obtained, while minimizing the cost and CO_2 emission. They find that a Multi-Objective Variable Neighborhood Search generally yields good results.

Li (2015) focused on solving the Travelling Salesman Problem while keeping the balance of minimizing the economic costs and the carbon emissions. He uses a market-dependent price for carbon permits. They find that carbon emissions can be visualized in a "ladder-type" decreasing curve. Emissions will decrease when the price of carbon permits is above a threshold.

3 Problem description

3.1 The Orienteering Problem with Hotel Selection

The goal of the orienteering problem with hotel selection is to maximize the score of the visited vertices. In the objective function, the score of the vertices is multiplied with the decision variable $x_{i,j,d}$. Where $x_{i,j,d}$ is equal to one if vertex j is visited directly after vertex i on day d. There are several restrictions, such as the maximum travel distance and starting and ending every trip in a hotel. There is a set of vertices, of size N and a set of hotels of size H. All hotels have a score of 0. In total there are $N + H$ nodes that can be visited. A tour consists of D days, and on every day there is exactly one trip. The trip has to start in one of the hotels and end in one of the hotels as well. The ending hotel can be the starting hotel. During the trip from one hotel to the next, the trip can visit vertices. A vertex can only be visited once, hotels can be visited more than once. It is assumed that every trip only uses one type of transportation, but that this can change throughout a tour.

This paper will use the same instances as given in the paper of A. Divsalar et al. (2013). Some quick analyses tell us that the trips vary in length between 0 and 65.1181. The length of the trip is denoted as the Euclidean distance. As the unit of the distance is not included anywhere, but given the range, in this paper is is assumed to be in kilometers. The lowest possible score of an individual vertex is 0 and the highest score of the vertices is 50. There are 144 trips with a distance of 0 and 31698 trips that have a distance larger than zero.

This paper will extend the OPHS with a penalty for the emission of CO_2. The objective of the model will remain the same, but the score obtained will be penalized. This penalty is dependent on the mode of transportation and the distance travelled. It is therefore calculated as $c_{i,j,v}$, the cost of traversing from vertex i to vertex j with transportation mode v.

3.2 Cost of CO_2

To measure the costs of the different modes of transportation, the values are obtained from the website of the Rijksoverheid of the Netherlands. Note here that these values can therefore be quite different when looking at other countries, as there can be differences in vehicles, roads and speed limits between countries. There are different parameters that contribute to the level of pollution of a vehicle. The Dutch government measures three different types of pollution. The first is the carbon dioxide (CO_2) emission. The second is nitrogen (NO_x) emission. The final contributor is the emission of fine particulates. This includes the fine particulates polluted by diesel engines and the wearing down of brakes, tires and road surfaces (Centraal Bureau voor de Statistiek, Planbureau voor de Leefomgeving, Rijksinstituut voor Volksgezondheid en Milieu & Wageningen University and Research, 2023). Figure 1 shows the development of environmental pressure in the Netherlands. It is clear to see that while the NO_x and fine particulates emission have decreased by 75% since 1990, the CO_2 emission seems to have only dropped below the level of 1990 due to the lock-downs of the Covid-19 pandemic. The Rijksoverheid has had extensive research done to find the different levels of emission and pollution. It has published an overview containing many types of transport (Geilenkirchen et al., 2023). For simplicity, this paper will

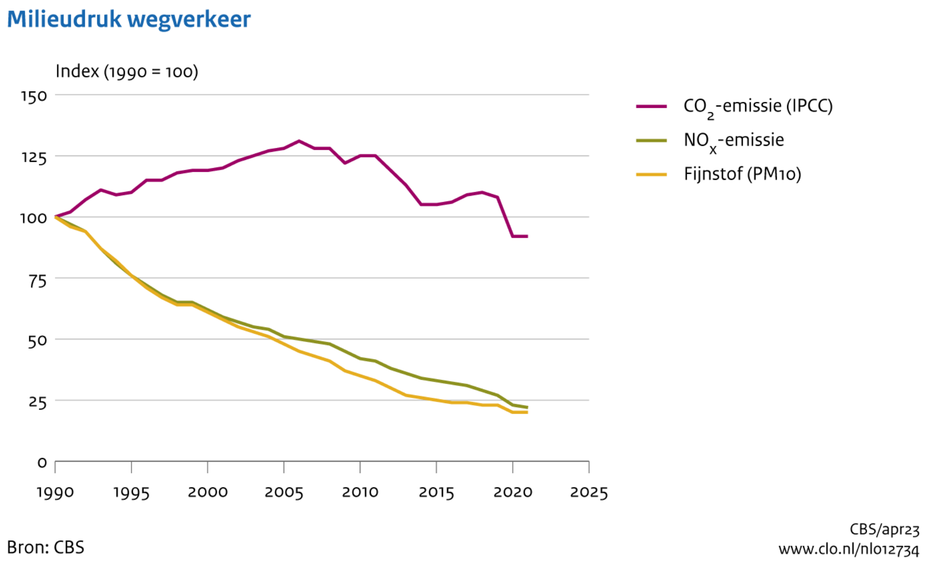

Figure 1: Environmental pressure on road-traffic in the Netherlands

only look at the CO_2 emission for the cost of travelling.

Milieu Centraal (n.d.) has created an overview of the CO_2 emission for twelve different modes of transportation. The CO_2 emission is only calculated for the use of the mode. The production of the vehicle and the building of the infrastructure are not taken into account. Four of these modes will be used to create the set V. The first mode is a bicycle, with an emission of 0 gram CO_2 per kilometer (km). The average speed of a bicycle is 12 km per hour (Molnár, 2002). Next, the electric scooter is included with an emission of 17 gram CO_2 per km. It is assumed to be a scooter with a blue license-plate, with a maximum speed of 25 km per hour. The average speed is set to 20 km per hour. The third vehicle is a car. As there are many different cars all with very different levels of emission, one will be selected. In this paper, the car is a petrol car with an emission of 149 gram CO_2 per km. This number is based on an average occupation per car of 1.3 people (Milieu Centraal, n.d.). The average speed of the car is defined by a piece wise function, as the speed is quite different depending on the length of the trip. Let d denote the length of the trip. The average speed of a car is given in Equation 1, this is an educated guess. Lastly, public transport is included in the modes of transportation. Similar to cars, the average speed is dependent on the length of the trip. The average speed of public transport is always below the speed of a car, but it is faster than the scooter. The emission is 96 gram CO_2 per km and the average speed is given in Equation 2.

$$\text{average speed car} = \begin{cases} 40 \text{ km per hour}, & \text{if } d < 20 \\ 60 \text{ km per hour}, & \text{if } 20 \leq d < 40 \\ 90 \text{ km per hour}, & \text{if } d > 40 \end{cases} \tag{1}$$

$$\text{average speed public transport} = \begin{cases} 30 \text{ km per hour}, & \text{if } d < 20 \\ 45 \text{ km per hour}, & \text{if } 20 \leq d < 40 \\ 70 \text{ km per hour}, & \text{if } d > 40 \end{cases} \tag{2}$$

All emissions are shown in Table 1. The speed of the modes of transportation is relative to the speed of the bicycle. The three speed levels for car and public transport are the relative speed levels depending on the three different categories in distance. As base mode of transportation, the bicycle is selected as this will infer no penalty on the original model. The allowed distance of the bicycle is exactly the daily limit in Euclidean distance.

Mode of transportation	CO_2 emission in grams	Speed (relative to bicycle)
Bicycle	0	1
Electric Scooter	17	2.09
Petrol Car	149	3.33; 5; 7.5
Public transport	96	2.5; 3.75; 5.83

Table 1: CO_2 emission per kilometer
(Milieu Centraal, n.d.)

The price of a ton of CO_2 emission is not immediately clear. Extensive research has been done by different parties, resulting in prices varying between €37 and €220 per ton of CO_2 (Klimaatplein, n.d.).

Nobel Prize winner Joseph Stiglitz and Lord Nicholas Stern found a price of €60 per ton of CO_2 needed to reach the goals of the Paris Climate Agreement, while the Obama government of the United States found a price of $43. Although he does not believe in climate change, Trump was obliged under the Clean Air Act to also estimate the social cost of carbon emissions. The Trump administration found a controversial cost of $3–$5 a ton. He managed to find a much lower price by not taking all negative effects of climate change into account. For example, the Trump administration only counted the climate damage in the U.S., and not the damage done to the rest of the world. Moreover, the Trump administration worked with a much higher discount rate, and thereby put much less weight on the future (Backman, 2021). The Biden administration did its own calculations on the social cost of CO_2 emissions and found a price of $51 per ton.

This clearly illustrates that the price of carbon emissions is strongly influenced by politics. Putting a price on emissions is relatively new and there are many ways to approach this. The European Union generally puts a higher price on the emission of CO_2, as can be seen from the prices put into effect in the EU.

Early this year, the price of the European Emission Trade System has reached €100 for the first time, and the expectation is that it will remain this high (Middelweerd, 23-02-2023). However, the current market price of emission rights for large industries of a ton of CO_2 in the European Union is set to €55,94. This will increase with €11,55 every year (Emissieautoriteit, 2023).

As the main application of this paper is the touristic sector, this paper will use the price of €100 for the emission of a ton of CO_2, resulting in a price of €0,0001 per gram of CO_2. The effect of setting the price to zero and increasing it is also analyzed.

4 Methodology

As explained in the previous section, a small set of modes of transportation is considered here, due to limited time available. As the main goal of maximizing the score should stay the same, the cost will be implemented in the model using a penalty. This penalty will be included in the objective function and will therefore decrease the cumulative score of the visited vertices. The objective function in the model maximizes the score of the visited nodes, where every node has a fixed score, with a deduction of the penalty for the CO_2 emission.

Adjusting for the different speeds of the different modes of transportation can be done by adjusting the needed travel time between vertices. The parameter $t_{i,j,v}$, which denotes the travelling time between two vertices i and j, can be different for the different modes of transportation v. It is independent on the day of travel.

The penalty is denoted per distance unit, and will therefore be multiplied with the distance of the trip. The cost of travelling from vertex i to vertex j with transportation mode v is given by $c_{i,j,v}$. This parameter was explained in Section 3.2.

To incorporate the penalty in the model some alterations need to be made. First, a parameter for costs is introduced. Let V denote the full set of transportation modes considered and $v \in V$. The penalty is included in the objective function. The score of a node will be decreased if the trip is made with a polluting transportation method. The new objective function is given in Equation 3. S_i is a parameter denoting the score of node i and $x_{i,j,d,v}$ is a binary decision variable that is equal to one if the trip on day d includes the arc between vertices i and j, traversed by transportation method v, and zero otherwise.

$$\max \sum_{v=1}^{V} \sum_{d=1}^{D} \sum_{i=0}^{H+N} \sum_{j=0}^{H+N} (S_i - c_{i,j,v}) x_{i,j,d} \tag{3}$$

A new constraint is introduced, that ensures that only one type of transportation is used in a trip. The binary variable $a_{d,v}$ is equal to one if a transportation method v is used on day d and zero otherwise. The constraint is given in Equation 4.

$$\sum_{v=1}^{V} a_{d,v} = 1 \text{ for every } d = 1, ..., D \tag{4}$$

The constraints from A. Divsalar et al. (2013) are also included, resulting in the following model:

$$\max \sum_{d=1}^{D} \sum_{i=0}^{H+N} \sum_{j=0}^{H+N} \sum_{v=1}^{V} (S_i - c_{i,j,v}) x_{i,j,d,v} \tag{5a}$$

$$\text{s.t.} \sum_{l=1}^{H+N} \sum_{v=1}^{V} x_{0,l,1,v} = 1 \tag{5b}$$

$$\sum_{k=0}^{H+N} \sum_{v=1}^{V} x_{k,1,D,v} = 1 \tag{5c}$$

$$\sum_{h=0}^{H}\sum_{l=0}^{H+N}\sum_{v=1}^{V} x_{h,l,d,v} = 1 \qquad d = 1,\dots,D \tag{5d}$$

$$\sum_{h=0}^{H}\sum_{k=0}^{H+N}\sum_{v=1}^{V} x_{k,h,d,v} = 1 \qquad d = 1,\dots,D \tag{5e}$$

$$\sum_{k=0}^{H+N}\sum_{v=1}^{V} x_{k,h,d,v} = \sum_{l=0}^{H+N}\sum_{v=1}^{V} x_{h,l,d+1,v} \qquad d = 1,\dots,D; \quad h = 0,\dots,H \tag{5f}$$

$$\sum_{i=0}^{H+N} x_{i,k,d,v} = \sum_{j=0}^{H+N} x_{k,j,d,v} \qquad d = 1,\dots,D; \quad k = H+1,\dots,H+N; \quad v = 1,\dots,V \tag{5g}$$

$$\sum_{d=1}^{D}\sum_{j=0}^{H+N}\sum_{v=1}^{V} x_{i,j,d,v} \leq 1 \qquad i = H+1,\dots,H+N \tag{5h}$$

$$\sum_{i=0}^{H+N}\sum_{j=0}^{H+N} t_{i,j,v} x_{i,j,d,v} \leq T_d \qquad d = 1,\dots,D; \quad v = 1,\dots,V \tag{5i}$$

$$u_i - u_j + 1 \leq (N-1)(1 - \sum_{d=0}^{D}\sum_{v=1}^{V} x_{i,j,d,v}) \qquad i,j = H+1,\dots,H+N \tag{5j}$$

$$\sum_{v=1}^{V} a_{d,v} = 1 \qquad d = 1,...,D \tag{5k}$$

$$x_{i,j,d,v} \leq a_{d,v} \qquad i,j = 1,\dots,H+N; \quad d = 1,\dots,D; \quad v = 1,\dots,V \tag{5l}$$

$$u_i \in \{1,\dots,N\} \qquad i = H+1,\dots,H+N \tag{5m}$$

$$x_{i,j,d,v} \in \{0,1\} \qquad \forall i,j = 0,\dots,H+N | i \neq j; \quad d = 1,\dots,D; \quad v = 1,\dots,V \tag{5n}$$

$$a_{d,v} \in \{0,1\} \qquad d = 1,\dots,D; \quad v = 1,\dots,V \tag{5o}$$

The objective function 5a maximizes the score minus the penalty for CO_2, as explained previously in Equation 3. The first set of constraints in Equation 5b ensures that the trip on the first day starts in hotel 0. The second set of constraints, Equation 5c, ensures that the last trip ends in hotel 1. Constraints 5d and 5e make sure that every trip starts and ends in a hotel respectively. Next, a trip should start in the hotel where the previous trip has ended, as is shown in Equation 5f. Connectivity is given through Equation 5g. Constraints 5h guarantees every vertex is only visited once. Next, Constraints 5i makes sure every trip stays within its time limit, denoted by T_d. Equation 5j defines the constraints for sub-tour elimination. Only one mode of transportation can be used in a trip, as denoted by Equation 5k. The decision variable $x_{i,j,d,v}$ is connected to $a_{d,v}$ through Equation 5l, such that if $x_{i,j,d,v}$ is equal to one on a day for a specific mode of transportation, $a_{d,v}$ will also be one. The last three constraints ensure that the variable u_i is an integer no larger than N and that $x_{i,j,d,v}$ and $a_{d,v}$ are binary.

The model is coded in Java using Eclipse 4.18 for Mac OS X. To optimize, ILOG CPLEX Optimization Studio is used. The model of A. Divsalar et al. (2013) is first replicated and will be denoted by 'replication' for further reference.

4.1 Standard Orienteering Problem with Hotel Selection

When the dimension of mode of transport would not be included, it would yield the model of A. Divsalar et al. (2013). This model is implemented in CPLEX, to compare results with the addition of the mode of transport. Moreover, this model is implemented in Java using a skewed variable neighbourhood search, following the methodology of A. Divsalar et al. (2013). An overview of this can be found in Appendix A. This heuristic finds a solution for the tour and aims to maximize the score. The value found is not always as high as the optimal value found using CPLEX, but the result is found much faster. The heuristic in the code attached to this paper does not find a solution as fast as A. Divsalar et al. (2013), but it was significantly faster than solving to optimality using CPLEX.

5 Results

The following tables show the results of the instances that found an optimal solution within 30 minutes. In Appendices C, D, E, and F all results are shown, including the ones that did not find an optimal solution within the time limit. Note that here the initial objectives can differ from the results shown in this section. In this section, the known objective values from A. Divsalar et al. (2013) are used to compare the initial objective values with the extension of the mode of transport. In the appendix the objective value found for the model of A. Divsalar et al. (2013) can deviate as in some situations the optimal value was not found within the time limit. In the appendix I have reported the best known solution found after 30 minutes. Note that for formatting reasons, public transport is denoted in the tables as PT. The first number of the name of the instance denotes the number of extra vertices (excluding the starting and ending hotel) and the second number is T_{max}, the total length of the tour. The results of SET1 with one extra hotel

Cost = €0,0001

Instance	Initial Obj	Obj	Day 1	Day 2	**% Δ Obj**
64-55	984	1344	Scooter	Scooter	36.6
64-70	1188	1344	Scooter	Scooter	13.1
64-75	1236	1344	Bicycle	Scooter	8.7
64-80	1284	1344	Bicycle	Scooter	4.7
66-60	915	1679	Scooter	Car	83.5
T1-65	240	285	Scooter	Bicycle	18.8
T1-70	260	285	Bicycle	Scooter	9.6
T1-73	265	285	Bicycle	Scooter	7.5
T1-75	270	285	Scooter	Bicycle	5.6
T1-80	280	285	Bicycle	Scooter	1.8
T1-85	285	285	Bicycle	Bicycle	0
T3-100	800	800	Bicycle	Bicycle	0
T3-105	800	800	Bicycle	Bicycle	0
T3-65	610	800	Scooter	Scooter	31.1
T3-75	670	800	Scooter	Bicycle	19.4
T3-80	710	800	Bicycle	Scooter	12.7
T3-85	740	800	Scooter	Bicycle	8.1
T3-90	770	800	Bicycle	Scooter	3.9
T3-95	790	800	Scooter	Bicycle	1.3

Table 2: SET1 1-2

and two trips are shown in Table 2. The first thing that becomes clear is that the bicycle and scooter are by far the most chosen modes of transport. Scooter is chosen 19 times and bicycle is chosen 18 times. Travelling by car is only chosen once and public transport is never chosen. The addition of the modes of transport increases the objective value in most situations. The objective values are rounded to integers. The largest increase appears in instance 66-60, where the increase is 83.5%. In the case the objective value is exactly the same, it is important to note that the first optimization (with a cost) already visited all the vertices and therefore the solution could not improve. The values of these cumulative scores can be found in Appendix B in Table 8.

		Cost = €0,00				Cost = €0,001				Cost = €0,01			
Instance	Initial Obj	Obj	Day 1	Day 2	% Δ Obj	Obj	Day 1	Day 2	% Δ Obj	Obj	Day 1	Day 2	% Δ Obj
64-55	984	1344	PT	PT	36.6	1342	Scooter	Scooter	36.4	1329	Scooter	Scooter	35.1
64-75	1236	1344	Scooter	Car	8.7	1343	Bicycle	Scooter	8.7				
64-80	1284	1344	Scooter	Car	4.7	1343	Bicycle	Scooter	4.6				
66-60	915	1680	Car	Car	83.6								
T1-65	240	285	PT	PT	18.8	284	Bicycle	Scooter	18.3	277	Bicycle	Scooter	6.4
T1-70	260	285	Car	PT	9.6	284	Bicycle	Scooter	9.2	277	Bicycle	Scooter	6.6
T1-73	265	285	Car	Scooter	7.5	284	Bicycle	Scooter	7,3	277	Bicycle	Scooter	6.7
T1-75	270	285	Car	Scooter	5.6	284	Bicycle	Scooter	5.3	278	Bicycle	Scooter	6.8
T1-80	280	285	PT	Bicycle	1.8	284	Bicycle	Scooter	1,5	280	Bicycle	Bicycle	0
T1-85	285	285	PT	Scooter	0	285	Bicycle	Bicycle	0	285	Bicycle	Bicycle	0
T3-100	800	800	PT	Car	0	800	Bicycle	Bicycle	0	800	Bicycle	Bicycle	0
T3-105	800	800	Scooter	Car	0	800	Bicycle	Bicycle	0	800	Bicycle	Bicycle	0
T3-65	610	800	PT	PT	31.1								
T3-75	670	800	Car	PT	19.4	799	Bicycle	Scooter	19,3	790	Bicycle	Scooter	17.9
T3-80	710	800	Car	PT	12.7	799	Bicycle	Scooter	12.5	790	Bicycle	Scooter	11.3
T3-85	740	800	PT	Bicycle	8.1	799	Bicycle	Scooter	8.0	791	Bicycle	Scooter	6.9
T3-90	770	800	Scooter	Scooter	3.9	799	Bicycle	Scooter	3,8	791	Bicycle	Scooter	2.7
T3-95	790	800	Car	Car	1.3	799	Bicycle	Scooter	1,2	791	Bicycle	Scooter	0.1

Table 3: SET1 1-2 with different costs

The results are also analyzed for different costs per gram of CO_2, these results can be found in Table 3. When the cost is neglected and set to zero, the objective values found are very similar to the results found with a cost of €0.0001. However, the mode of transport is often different in this new situation. When the cost are not taken into account, the car and public transport are chosen much more often than before. In SET1 1-2 the car is chosen 14 times in the situation with no cost, when it was only chosen once when there was a cost included. The same holds for public transport, that is now chosen 13 times and was not chosen at all before. The use of the bicycle and scooter is reduced a lot. The bicycle is now only chosen twice, which is a decrease of 89%. The scooter is chosen 9 times, which is a decrease of 53%. In SET1 1-2 there are three trips where there is no improvement, as all vertices are already visited in the original situation (without choice of transport).

Next, the results are analyzed for a cost ten times as large. Finally, the same problem is solved but with a cost of a hundred times as large. The results for the different costs can be found in Table 3. Some values for the cost of €0,01 per gram CO_2 are missing, as the computer did not find an optimal solution for these instances within the time limit of 30 minutes. When the costs are increased with a factor of ten, the bicycle and scooter are the only modes of transportation. The difference between a cost ten times as large and a cost a hundred times as large is not very visible. There is one trip that has changed from scooter to bicycle.

Table 4 shows the results of SET1 with two extra hotels and three trips with a cost of €0.0001 per gram CO_2. Again, bicycle and scooter are often the optimal modes of transport, with bicycle chosen 24 times and scooter chosen 23 times. Car is once the optimal mode of transport and public transport is never the best option.

Again there is one situation where there is no improvement possible, in instance T1-85. In the instances T3-100 and T3-105, the change in objective value is very small.

In Table 5 the effects of neglecting the cost are comparable to the situation with two trips. Again car and public transport are chosen much more often. The car is now chosen 17 times and public transport is chosen 18 times. The bicycle is only chosen four times and scooter is chosen

		Cost = €0.0001				
Instance	Initial Obj	Obj	Day 1	Day 2	Day 3	% Δ Obj
64-60	1062	1.344	Bicycle	Scooter	Scooter	26.6
64-65	1116	1.344	Scooter	Scooter	Scooter	20.4
66-60	915	1.679	Scooter	Scooter	Car	83.5
T1-70	260	285	Bicycle	Bicycle	Scooter	9.6
T1-73	265	285	Bicycle	Bicycle	Scooter	7.5
T1-75	270	285	Bicycle	Bicycle	Scooter	5.6
T1-80	280	285	Bicycle	Bicycle	Scooter	1.8
T1-85	285	285	Bicycle	Bicycle	Bicycle	0
T3-100	800	800	Bicycle	Bicycle	Scooter	0[1]
T3-105	800	800	Scooter	Bicycle	Bicycle	0[2]
T3-65	610	800	Scooter	Scooter	Scooter	31.1
T3-75	670	800	Scooter	Bicycle	Bicycle	19.4
T3-80	710	800	Bicycle	Scooter	Scooter	12.7
T3-85	740	800	Bicycle	Bicycle	Scooter	8.1
T3-90	770	800	Bicycle	Scooter	Bicycle	3.9
T3-95	790	800	Bicycle	Scooter	Bicycle	1.3

[1] Here it seems as if the use of a scooter for the trip on the first day does not decrease the objective value. This is remarkable as the use of the scooter should come with a cost. This can by explained by the fact that in the table all objectives are rounded to integers, the objective value for this instance is 799.9264169204685, not rounded off. The effect of taking the scooter on this day is very small. It only decreases the objective value with 0.07358307953 , that is a decrease of 0.0092%.

[2] The same occurs for the instance T3-100, where new objective is 799.9261485057086, that is a decrease of 0.0092%.

Table 4: SET1 2-3

8 times. The trips by bicycle have decreased by 83% and the use of the scooter has decreased by 65%. When the cost is ten times as large, the bicycle and scooter are the only modes of transport selected.

		Cost = €0.00					Cost = €0.001				
Instance	Initial Obj	Obj	Day 1	Day 2	Day 3	% Δ Obj	Obj	Day 1	Day 2	Day 3	% Δ Obj
64-60	1062	1344	Scooter	Car	Bicycle	26.6					
64-65	1116	1344	Car	Car	Scooter	20.4					
66-60	645	1680	Car	Car	Car	83.6					
T1-70	260	285	Car	Car	Bicycle	9.6	284	Bicycle	Bicycle	Scooter	9.2
T1-73	265	285	PT	PT	PT	7,5	284	Bicycle	Bicycle	Scooter	7.2
T1-75	270	285	Car	PT	PT	5.6	284	Bicycle	Bicycle	Scooter	5.2
T1-80	280	285	Scooter	PT	PT	1.8	284	Bicycle	Bicycle	Scooter	1.4
T1-85	285	285	Car	PT	Scooter	0	285	Bicycle	Bicycle	Bicycle	0
T3-100	800	800	Scooter	PT	Scooter	0	800	Bicycle	Bicycle	Bicycle	0
T3-105	790	800	Car	PT	Car	0	800	Bicycle	Bicycle	Bicycle	1,3
T3-65	610	800	PT	Car	Bicycle	31.1					
T3-75	670	800	PT	PT	PT	19.4	799	Scooter	Bicycle	Bicycle	19.3
T3-80	710	800	Scooter	Car	Scooter	12.7					
T3-85	740	800	Car	Scooter	Car	8.1	799	Bicycle	Bicycle	Scooter	8.0
T3-90	770	800	PT	PT	PT	3.9					
T3-95	790	800	Car	PT	Bicycle	1.3					

Table 5: SET1 2-3 with different costs

For the situation in SET1 with three extra hotels and four trips, as can be found in Table 6, both car and public transport are both never the optimal mode of transport. Scooter is 17 times the best option and bicycle 27 times.

When the cost is set to zero, the shift from bicycle and scooter to car is again very apparent. Car is now 39 times the chosen mode of transportation. It is noticeable that here public transport is only once chosen as mode of transportation. Bicycle is also chosen once, which is a decrease of 96%, and scooter is chosen three times, which is a decrease of 82%.

For the cost ten times as large, only a few instances found an optimal solution within half

Instance	Initial Obj	Cost = €0.0001					
		Obj	Day 1	Day 2	Day 3	Day 4	% Δ Obj
64-70	1188	1.344	Scooter	Bicycle	Bicycle	Scooter	13.1
T1-70	260	285	Bicycle	Bicycle	Bicycle	Scooter	9.6
T1-73	265	285	Bicycle	Scooter	Bicycle	Bicycle	7.5
T1-80	280	285	Bicycle	Bicycle	Bicycle	Scooter	1.8
T3-100	800	800	Bicycle	Bicycle	Bicycle	Scooter	0[3]
T3-105	800	800	Bicycle	Bicycle	Bicycle	Scooter	0[4]
T3-65	610	800	Scooter	Scooter	Scooter	Bicycle	31.1
T3-75	670	800	Scooter	Scooter	Bicycle	Scooter	19.4
T3-80	710	800	Scooter	Bicycle	Scooter	Bicycle	12.7
T3-90	770	800	Bicycle	Bicycle	Bicycle	Scooter	3.9
T3-95	790	800	Scooter	Bicycle	Bicycle	Bicycle	1.3

[3] In the instance T3-100, the use of the scooter seems to again have no effect on the objective value. The same explanation can be given as in the situation with two additional hotels and three trips, as the objectives are again very close to 800. They are 799.9386322513442 and respectively, when not rounded off. The decrease in the objective is 0.0077%.

[4] The same holds for T3-105, with a new objective of 799.9399012326348 and therefore a decrease of 0.0075%.

Table 6: SET1 3-4

an hour. These few solutions use the bicycle and scooter as modes of transport.

Instance	Initial Obj	Cost = €0.00						Cost = €0.001					
		Obj	Day 1	Day 2	Day 3	Day 4	% Δ Obj	Obj	Day 1	Day 2	Day 3	Day 4	% Δ Obj
64-70	1188	1344	Car	Car	Bicycle	Car	13.1						
T1-70	260	285	Car	Car	Car	Car	9.6	285	Bicycle	Bicycle	Bicycle	Scooter	9.6
T1-73	265	285	Car	Car	Car	Car	7.5						
T1-80	280	285	Car	Car	PT	Car	1.8	285	Bicycle	Bicycle	Bicycle	Scooter	1.8
T3-100	800	800	Car	Car	Car	Car	0	800	Bicycle	Bicycle	Bicycle	Bicycle	0
T3-105	790	800	Car	Car	Car	Car	1.3						
T3-65	610	800	Car	Car	Car	Scooter	31.1						
T3-75	670	800	Car	Car	Car	Scooter	19.4						
T3-80	710	800	Car	Scooter	Car	Car	12.7						
T3-90	770	800	Car	Car	Car	Car	3.9						
T3-95	790	800	Car	Car	Car	Car	1.3						

Table 7: SET1 3-4 with different costs

In short, in nearly all instances, the objective value is either improved or remained the same compared to the model without choice of transportation. Only for the instances T3-100-2-3 and T3-100-3-4 has it decreased slightly. The largest increases occur in the instances with a smaller T_{max} parameter. In SET1 1-2 these are instances 64-55, 66-60, and T3-65, with increases of 37%, 84% and 31% respectively. In SET1 2-3 the instance 64-60 has a relatively high increase. Again an instance with a small value for T_{max}. The same holds for SET1 3-4, although the improvements seem to moderate here a little.

6 Conclusion

This paper aims to answer the following research question:

> What is the effect of implementing a penalty in the model of A. Divsalar et al. (2013) to account for the CO_2 emission of the transportation used in the orienteering problem with hotel selection?

By comparing the results with a cost of €0.0001 per gram of CO_2 and the results where the cost is set to zero, it becomes clear that this cost has already quite a strong effect on the modes of transportation chosen. The main modes of transport without a cost are the car and public transport, while with a cost, there is a strong shift towards the bicycle and scooter. Without a cost, the objective value is always equal to the maximum score that can be obtained, meaning that all vertices are visited. When the cost is implemented, the objective values decrease in some situations, but in many instances the objective value is still the maximum possible score. This means that the cost of travelling with the scooter or car in these situations is negligible. In all instances, the objective value is still larger than it was in the situation of A. Divsalar et al. (2013).

When the cost is increased with a factor of ten, the bicycle is chosen as mode of transport more often. The objective values are still higher than they were in the original situation.

For SET1 1-2 the cost is also multiplied by a hundred. The effect of this is that in one trip (out of the 28 trips analyzed) the scooter is substituted with a bicycle. The effect of this does therefore not seem to be as strong as the first increase in the cost, where the cost is multiplied by ten.

The largest improvements in the objective values are found when the total trip length, T_{max}, is relatively small, compared to the number of vertices. In these situations a faster mode of transport can really attribute to the score obtained, as there is less time to visit the vertices. In the instances with a larges value for T_{max}, the initial objective values come closer to the maximum possible score that can be obtained. Here it is relevant to note that when T_{max} is larger, the initial objective value was already closer to the maximum possible score and the same relative increase is simply not possible.

In conclusion, a cost of €0.0001 per gram emission of CO_2 is already an incentive to choose for the bicycle and scooter as mode of transportation more often than the car and public transport. Passing on the external costs of the emission of CO_2 to the consumer in the form of a CO_2 tax, is an efficient method to decrease the emission of CO_2, because the modes of transportation with low emission become more profitable.

Extending the model of A. Divsalar et al. (2013) with a penalty to account for the CO_2 emission of transportation results in more intricate selection of transportation, where often the more environmentally favourable mode of transportation is chosen.

7 Discussion

This research is done in a time span of ten weeks and will therefore have some limitations to it.

First, this paper makes use of a selected set of vehicles. It will generalize multiple cars into the same category, while in reality there are many different types of cars that could all have quite different levels of emission. Depending on the application, the set of vehicles can differ in composition and size. Moreover, the assumption is made that a trip is made using only one method of transportation. There are definitely applications where this does not have to be the case and this would be interesting to investigate.

Furthermore, only the emission of the vehicle while driving or riding is taken into account here, but there are other factors, such as production cost and the use of recyclable materials or maybe even noise pollution that can also be relevant.

Moreover, it is assumed that the modes of transportation can be changed in every hotel. To come closer to reality, it could be interesting to incorporate the situation where not every vehicle is available at every hotel or maybe cannot be left behind at every hotel.

The implementation of the modes of transportation in this paper is done in CPLEX. Although CPLEX finds optimal solutions, it does not solve very fast. Because of the time limitations, only a selected set of instances is solved. The limit to find an optimal solution was set to half an hour. For the instances that did not have a solution after this time, the best known feasible value is reported in the appendix, but it would be interesting to know what their optimal solution is.

Also, a good next step would be to implement the additional of choice of transportation to the heuristic method developed by A. Divsalar et al. (2013). This will help find solutions for more instances much faster.

This paper analyzes the current price of the emission of CO_2 enforced in the EU. As explained in Section 3.2, the price of CO_2 is still very politically motivated. Therefore it is quite hard to justify a chosen price, as there are many different opinions on what this price should be.

Moreover, when taking a car or scooter, taking into account traffic jams and rush hours can be a nice addition to this problem, as this could influence the choice of transportation, as this effects both the speed and traffic jams tend to cause for higher CO_2 emissions.

References

Ataei, M., Divsalar, A. & Saberi, M. (2022). The bi-objective orienteering problem with hotel selection: an integrated text mining optimisation approach. *Information Technology and Management*. Retrieved from www.scopus.com

Backman, I. (2021, Jun). *Professors explain the social cost of carbon.* Stanford University. Retrieved from https://news.stanford.edu/2021/06/07/professors-explain-social-cost-carbon/

Centraal Bureau voor de Statistiek, Planbureau voor de Leefomgeving, Rijksinstituut voor Volksgezondheid en Milieu & Wageningen University and Research. (2023). *Wegverkeer: volumeontwikkeling en milieudruk, 1990-2021.* https://www.clo.nl/indicatoren/nl0127-wegverkeer-volumeontwikkeling-en-milieudruk. (Accessed: 04-05-2023)

Divsalar, A., Vansteenwegen, P. & Cattrysse, D. (2013). A variable neighborhood search method for the orienteering problem with hotel selection. *International Journal of Production Economics*, *145*(1), 150-160.

Divsalar, A., Vansteenwegen, P., Sörensen, K. & Cattrysse, D. (2014). A memetic algorithm for the orienteering problem with hotel selection. *European Journal of Operational Research*, *237*, 29-49.

Divsalar, G., Divsalar, A., Jabbarzadeh, A. & Sahebi, H. (2022). An optimization approach for green tourist trip design. *Soft Computing*, *26*(9), 4303-4332.

Emissieautoriteit, N. (2023, Jan). *Tarieven co2-heffing.* Author. Retrieved from https://www.emissieautoriteit.nl/onderwerpen/tarieven-co2-heffing

Garcia, A., Linaza, M. T., Arbelaitz, O. & Vansteenwegen, P. (2009). *Information and communication technologies in tourism 2009: Intelligent routing system for a personalised electronic tourist guide.*

Geilenkirchen, G., Bolech, M., Hulskotte, J., Dellaert, S., Ligterink, N., Sijstermans, M., ... 't Hoen, M. (2023). Methods for calculating the emissions of transport in the netherlands.

Gunawan, A., Lau, H. C. & Vansteenwegen, P. (2016). Orienteering problem: A survey of recent variants, solution approaches and applications. *European Journal of Operational Research*, *255*(2), 315-332.

Klimaatplein. (n.d.). *De maatschappelijke kosten van klimaatverandering.* https://www.klimaatplein.com/de-maatschappelijke-kosten-van-klimaatverandering/. (Accessed: 30-05-2023)

Li, J. (2015). Carbon footprint management of road freight transport under the carbon emission trading mechanism. *Mathematical Problems in Engineering*. doi: 10.1155/2015/814527

Middelweerd, H. (23-02-2023). *Mijlpaal: Europese co2-prijs voor het eerst boven de 100 euro per ton.* https://www.change.inc/finance/mijlpaal-europese-co2-prijs-voor-het-eerst-boven-de-100-euro-per-ton-39611. (Accessed: 01-06-2023)

Milieu Centraal. (n.d.). *Co2-uitstoot fiets, ov en auto.* https://www.milieucentraal.nl/duurzaam-vervoer/co2-uitstoot-fiets-ov-en-auto/.

(Accessed: 16-05-2023)

Molnár, H. (2002). Fietsend achterop. `https://www.cbs.nl/nl-nl/achtergrond/2002/36/fietsend-achterop`.

Ruiz-Meza, J. & Montoya-Torres, J. R. (2022). A systematic literature review for the tourist trip design problem: Extensions, solution techniques and future research lines. *Operations Research Perspectives*, *9*. Retrieved from `www.scopus.com` (Cited By :8)

Sohrabi, S., Ziarati, K. & Keshtkaran, M. (2020). A greedy randomized adaptive search procedure for the orienteering problem with hotel selection. *European Journal of Operational Research*, *283*(2), 426-440. doi: https://doi.org/10.1016/j.ejor.2019.11.010

Sohrabi, S., Ziarati, K. & Keshtkaran, M. (2021). Acs-ophs: Ant colony system for the orienteering problem with hotel selection. *EURO Journal on Transportation and Logistics*, *10*.

Toledo, A., Riff, M.-C. & Neveu, B. (2020). A hyper-heuristic for the orienteering problem with hotel selection. *IEEE Access*, *8*, 1303-1313. doi: 10.1109/ACCESS.2019.2960492

Vansteenwegen, P., Souffriau, W. & Oudheusden, D. V. (2011). The orienteering problem: A survey. *European Journal of Operational Research*, *209*(1), 1-10.

Vathis, N., Konstantopoulos, C., Pantziou, G. & Gavalas, D. (2023). The vacation planning problem: A multi-level clustering-based metaheuristic approach. *Computers Operations Research*, *150*.

A Overview of the Code

For the implementation of this model, I have coded in Java using both Eclipse and IntelliJ. The implementation consists of seven classes. I will discuss them here in alphabetical order.

First is the CPLEX class. Here two models are implemented using CPLEX. If you were to run this class yourself, know that you have to download CPLEX and add the CPLEX library to your Java project in order to use this solver. The first model, denotes as OPHSRep, is the replication of the model of A. Divsalar et al. (2013). Next the model with the extension of the choice of transportation is coded, denoted as OPHS.

The next class is the subOP class. This class finds the best trip between two hotels. The class consists of two methods, first the subOP() method, where the greedy subOP heuristic is executed. The second method is the getSubOP(), this method is simply used to return the found subOP in the type of a Trip.

The SVNS class can be seen as the main method that executes the skewed variable neighborhood search. This class reads in the data, in the same way as in the CPLEX class. The code from the CPLEX class to read the zip-file can be copied here to read in all files at once. Per dataset, a three-dimensional matrix is created in which all pairs of hotels and their subOP is stored. Then all combinations of hotels are selected that form a feasible tour. After this all feasible tours are improved using local search, hotels-shake and vertices-shake. Whenever a solution is found that improves the previous solution, this solution is taken and used for further improvement.

The Tour class creates a Tour, which consists of an ArrayList of Trips, an ArrayList of all vertices and some other characteristics of the tour. This class has some methods, such as doLocalSearch() and doHotelShake(), to execute the SVNS. Moreover, some of the methods from the local search, that influence the whole tour, are also defined in this class: Insert(), MoveBest(), and SwapTrips() can be found here. The remaining methods are methods to obtain some information about the tour or to make small adjustments, such as inserting or removing a vertex.

The Transport class is used to create the possible modes of transportation. Every transportation mode has its own name, speed and CO_2 emission. The speed for the car and public transport is dependent on the size of the trip.

The class for Trip is quite similar to the Tour class, only here all methods are specified for a single trip. Here you can find the methods of the local search that only have an effect on one trip: TwoOpt(), Replacement(), and the Extract-Insert methods. Also the method insertMinDist() is defined here. This method finds the best location in a trip for a vertex, this method is often used in the moves of the local search, such as Insert(), MoveBest() and the Extract-Insert methods.

The final class is the Vertex class, where a single vertex is defined. A vertex has an index, an x-coordinate, a y-coordinate, and a score.

B Cumulative Score of Instances

Instance	Cumulative score	Instance	Cumulative score	Instance	Cumulative score
1-2/100-30	1306.0	2-3/100-30	1306.0	3-4/100-30	1306.0
1-2/100-35	1306.0	2-3/100-35	1306.0	3-4/100-35	1306.0
1-2/100-40	1306.0	2-3/100-40	1306.0	3-4/100-40	1306.0
1-2/100-45	1306.0	2-3/100-45	1306.0	3-4/100-45	1306.0
1-2/102-50	1458.0	2-3/102-50	1458.0	3-4/102-50	1458.0
1-2/102-60	1458.0	2-3/102-60	1458.0	3-4/102-60	1458.0
1-2/64-45	1344.0	2-3/64-45	1344.0	3-4/64-45	1344.0
1-2/64-50	1344.0	2-3/64-50	1344.0	3-4/64-50	1344.0
1-2/64-55	1344.0	2-3/64-55	1344.0	3-4/64-55	1344.0
1-2/64-60	1344.0	2-3/64-60	1344.0	3-4/64-60	1344.0
1-2/64-65	1344.0	2-3/64-65	1344.0	3-4/64-65	1344.0
1-2/64-70	1344.0	2-3/64-70	1344.0	3-4/64-70	1344.0
1-2/64-75	1344.0	2-3/64-75	1344.0	3-4/64-75	1344.0
1-2/64-80	1344.0	2-3/64-80	1344.0	3-4/64-80	1344.0
1-2/66-125	1680.0	2-3/66-125	1680.0	3-4/66-125	1680.0
1-2/66-130	1680.0	2-3/66-130	1680.0	3-4/66-130	1680.0
1-2/66-40	1680.0	2-3/66-40	1680.0	3-4/66-40	1680.0
1-2/66-45	1680.0	2-3/66-45	1680.0	3-4/66-45	1680.0
1-2/66-50	1680.0	2-3/66-50	1680.0	3-4/66-50	1680.0
1-2/66-55	1680.0	2-3/66-55	1680.0	3-4/66-55	1680.0
1-2/66-60	1680.0	2-3/66-60	1680.0	3-4/66-60	1680.0
1-2/T1-65	285.0	2-3/T1-65	285.0	3-4/T1-65	285.0
1-2/T1-70	285.0	2-3/T1-70	285.0	3-4/T1-70	285.0
1-2/T1-73	285.0	2-3/T1-73	285.0	3-4/T1-73	285.0
1-2/T1-75	285.0	2-3/T1-75	285.0	3-4/T1-75	285.0
1-2/T1-80	285.0	2-3/T1-80	285.0	3-4/T1-80	285.0
1-2/T1-85	285.0	2-3/T1-85	285.0	3-4/T1-85	285.0
1-2/T3-100	800.0	2-3/T3-100	800.0	3-4/T3-100	800.0
1-2/T3-105	800.0	2-3/T3-105	800.0	3-4/T3-105	800.0
1-2/T3-65	800.0	2-3/T3-65	800.0	3-4/T3-65	800.0
1-2/T3-75	800.0	2-3/T3-75	800.0	3-4/T3-75	800.0
1-2/T3-80	800.0	2-3/T3-80	800.0	3-4/T3-80	800.0
1-2/T3-85	800.0	2-3/T3-85	800.0	3-4/T3-85	800.0
1-2/T3-90	800.0	2-3/T3-90	800.0	3-4/T3-90	800.0
1-2/T3-95	800.0	2-3/T3-95	800.0	3-4/T3-95	800.0

Table 8: The cumulative score of all the vertices in the instances in SET1

C Results with cost of €0.0001

The following three tables show the results of SET1 with a cost of €0.0001 per gram emission of CO_2.

Instance	Old Obj	New Obj	Day 1	Day 2
100-30-1-2	173	673		
100-35-1-2	241	551		
100-40-1-2	299	850		
100-45-1-2	367	905		
102-50-1-2	155	446		
102-60-1-2	243	601		
64-45-1-2	816	1.331		
64-50-1-2	882	1.332		
64-55-1-2	978	1.344	Scooter	Scooter
64-60-1-2	1062	1.343		
64-65-1-2	1116	1.332		
64-70-1-2	1170	1.344	Scooter	Scooter
64-75-1-2	1236	1.344	Bicycle	Scooter
64-80-1-2	1248	1.344	Bicycle	Scooter
66-125-1-2	1635	1.680		
66-130-1-2	1615	1670		
66-40-1-2	510	1.133		
66-45-1-2	645	1.638		
66-50-1-2	675	1.634		
66-55-1-2	635	1.669		
66-60-1-2	780	1.679	Scooter	Car
T1-65-1-2	240	285	Scooter	Bicycle
T1-70-1-2	260	285	Bicycle	Scooter
T1-73-1-2	265	285	Bicycle	Scooter
T1-75-1-2	270	285	Scooter	Bicycle
T1-80-1-2	280	285	Bicycle	Scooter
T1-85-1-2	285	285	Bicycle	Bicycle
T3-100-1-2	800	800	Bicycle	Bicycle
T3-105-1-2	800	800	Bicycle	Bicycle
T3-65-1-2	610	800	Scooter	Scooter
T3-75-1-2	670	800	Scooter	Bicycle
T3-80-1-2	710	800	Bicycle	Scooter
T3-85-1-2	740	800	Scooter	Bicycle
T3-90-1-2	770	800	Bicycle	Scooter
T3-95-1-2	790	800	Scooter	Bicycle

Table 9: The output of SET1 1-2, when there are no modes of transportation given the program was terminated before an optimal solution was found.

Instance	Old Obj	New Obj	Day 1	Day 2	Day 3
100-30-2-3	173	593			
100-35-2-3	241	646			
100-40-2-3	299	778			
100-45-2-3	367	724			
102-50-2-3	181	426			
102-60-2-3	243	476			
64-45-2-3	816	1.295			
64-50-2-3	852	1.331			
64-55-2-3	972	1.343			
64-60-2-3	1062	1.344	Bicycle	Scooter	Scooter
64-65-2-3	1116	1.344	Scooter	Scooter	Scooter
64-70-2-3	1170	1.320			
64-75-2-3	1206	1.338			
64-80-2-3	1284	1.338			
66-125-2-3	1585	1590			
66-130-2-3	1375	1615			
66-40-2-3	570	1.223			
66-45-2-3	620	1.508			
66-50-2-3	675	1.654			
66-55-2-3	825	1.614			
66-60-2-3	635	1.679	Scooter	Scooter	Car
T1-65-2-3	240	285			
T1-70-2-3	260	285	Bicycle	Bicycle	Scooter
T1-73-2-3	265	285	Bicycle	Bicycle	Scooter
T1-75-2-3	270	285	Bicycle	Bicycle	Scooter
T1-80-2-3	280	285	Bicycle	Bicycle	Scooter
T1-85-2-3	285	285	Bicycle	Bicycle	Bicycle
T3-100-2-3	800	800	Bicycle	Bicycle	Scooter
T3-105-2-3	790	800	Scooter	Bicycle	Bicycle
T3-65-2-3	610	800	Scooter	Scooter	Scooter
T3-75-2-3	670	800	Scooter	Bicycle	Bicycle
T3-80-2-3	710	800	Bicycle	Scooter	Scooter
T3-85-2-3	740	800	Bicycle	Bicycle	Scooter
T3-90-2-3	770	800	Bicycle	Scooter	Bicycle
T3-95-2-3	790	800	Bicycle	Scooter	Bicycle

Table 10: The output of SET1 2-3, when there are no modes of transportation given the program was terminated before an optimal solution was found.

Instance	Inital Obj	New Obj	Day 1	Day 2	Day 3
100-30-3-4	173	608			
100-35-3-4	241	692			
100-40-3-4	299	169			
100-45-3-4	367	652			
102-50-3-4	181	437			
102-60-3-4	243	452			
64-45-3-4	816	1.206			
64-50-3-4	864	1.295			
64-55-3-4	822	1.200			
64-60-3-4	948	1.128			
64-65-3-4	1116	1.266			
64-70-3-4	1026	1.344	Scooter	Bicycle	Bicycle
64-75-3-4	960	1.308			
64-80-3-4	1098	1.313			
66-125-3-4	1405	1.680			
66-130-3-4	1370	1.679			
66-40-3-4	570	1.328			
66-45-3-4	645	1.414			
66-50-3-4	715	1.374			
66-55-3-4	825	1.489			
66-60-3-4	725	1.490			
T1-65-3-4	240	285			
T1-70-3-4	260	285	Bicycle	Bicycle	Bicycle
T1-73-3-4	265	285	Bicycle	Scooter	Bicycle
T1-75-3-4	270	285			
T1-80-3-4	280	285	Bicycle	Bicycle	Bicycle
T1-85-3-4	285	285			
T3-100-3-4	800	800	Bicycle	Bicycle	Bicycle
T3-105-3-4	730	800	Bicycle	Bicycle	Bicycle
T3-65-3-4	610	800	Scooter	Scooter	Scooter
T3-75-3-4	610	800	Scooter	Scooter	Bicycle
T3-80-3-4	710	800	Scooter	Bicycle	Scooter
T3-85-3-4	740	800			
T3-90-3-4	770	800	Bicycle	Bicycle	Bicycle
T3-95-3-4	790	800	Scooter	Bicycle	Bicycle

Table 11: The output of SET1 3-4, when there are no modes of transportation given the program was terminated before an optimal solution was found.

D Results without cost for emission of CO_2

The following three tables show the results of SET1 with no cost for the emission of CO_2.

Instances	Initial Obj	New obj	Day 1	Day 2
1-2/100-30-1-2	173	849		
1-2/100-35-1-2	241	512		
1-2/100-40-1-2	299	849		
1-2/100-45-1-2	367	1157		
1-2/102-50-1-2	155	669		
1-2/102-60-1-2	243	911		
1-2/64-45-1-2	816	1344	Car	Scooter
1-2/64-50-1-2	882	1344	Car	Car
1-2/64-55-1-2	978	1344	Public Transport	Public Transport
1-2/64-60-1-2	1062	1344	Car	Car
1-2/64-65-1-2	1116	1344	Scooter	Car
1-2/64-70-1-2	1170	1344	Scooter	Car
1-2/64-75-1-2	1236	1344	Scooter	Car
1-2/64-80-1-2	1248	1344	Scooter	Car
1-2/66-125-1-2	1630	1680	Scooter	Car
1-2/66-130-1-2	1600	1680	Bicycle	Public Transport
1-2/66-40-1-2	495	1675		
1-2/66-45-1-2	645	1680	Car	Car
1-2/66-50-1-2	545	1680	Car	Car
1-2/66-55-1-2	650	1680	Car	Car
1-2/66-60-1-2	780	1680	Car	Car
1-2/T1-65-1-2	240	285	Public Transport	Public Transport
1-2/T1-70-1-2	260	285	Car	Public Transport
1-2/T1-73-1-2	265	285	Car	Scooter
1-2/T1-75-1-2	270	285	Car	Scooter
1-2/T1-80-1-2	280	285	Public Transport	Bicycle
1-2/T1-85-1-2	284	285	Public Transport	Scooter
1-2/T3-100-1-2	800	800	Public Transport	Car
1-2/T3-105-1-2	800	800	Scooter	Car
1-2/T3-65-1-2	610	800	Public Transport	Public Transport
1-2/T3-75-1-2	670	800	Car	Public Transport
1-2/T3-80-1-2	710	800	Car	Public Transport
1-2/T3-85-1-2	740	800	Public Transport	Bicycle
1-2/T3-90-1-2	770	800	Scooter	Scooter
1-2/T3-95-1-2	790	800	Car	Car

Table 12: The results of SET1 1-2, when there are no modes of transportation given the program was terminated before an optimal solution was found.

Instances	**Initial Obj**	**New Obj**	**Day 1**	**Day 2**	**Day 3**
2-3/100-30-2-3	173	636			
2-3/100-35-2-3	241	676			
2-3/100-40-2-3	299	457			
2-3/100-45-2-3	367	434			
2-3/102-50-2-3	181	502			
2-3/102-60-2-3	243	654			
2-3/64-45-2-3	816	1338			
2-3/64-50-2-3	858	1332			
2-3/64-55-2-3	972	1344	Car	Public Transport	Car
2-3/64-60-2-3	1062	1344	Scooter	Car	Bicycle
2-3/64-65-2-3	1116	1344	Car	Car	Scooter
2-3/64-70-2-3	1170	1344	Public Transport	Public Transport	Car
2-3/64-75-2-3	1206	1344	Public Transport	Car	Public Transport
2-3/64-80-2-3	1284	1344	Public Transport	Car	Bicycle
2-3/66-125-2-3	1555	1680	Public Transport	Scooter	Scooter
2-3/66-130-2-3	1375	1680	Public Transport	Public Transport	Bicycle
2-3/66-40-2-3	570	1565			
2-3/66-45-2-3	620	1645			
2-3/66-50-2-3	675	1590			
2-3/66-55-2-3	825	1680	Car	Car	Car
2-3/66-60-2-3	635	1680	Car	Car	Car
2-3/T1-65-2-3	240	285	Public Transport	Car	Public Transport
2-3/T1-70-2-3	260	285	Car	Car	Bicycle
2-3/T1-73-2-3	265	285	Public Transport	Public Transport	Public Transport
2-3/T1-75-2-3	270	285	Car	Public Transport	Public Transport
2-3/T1-80-2-3	280	285	Scooter	Public Transport	Public Transport
2-3/T1-85-2-3	285	285	Car	Public Transport	Scooter
2-3/T3-100-2-3	800	800	Scooter	Public Transport	Scooter
2-3/T3-105-2-3	790	800	Car	Public Transport	Car
2-3/T3-65-2-3	610	800	Public Transport	Car	Bicycle
2-3/T3-75-2-3	670	800	Public Transport	Public Transport	Public Transport
2-3/T3-80-2-3	710	800	Scooter	Car	Scooter
2-3/T3-85-2-3	740	800	Car	Scooter	Car
2-3/T3-90-2-3	770	800	Public Transport	Public Transport	Public Transport
2-3/T3-95-2-3	790	800	Car	Public Transport	Bicycle

Table 13: The results of SET1 2-3, when there are no modes of transportation given the program was terminated before an optimal solution was found.

Instances	Initial Obj	New obj	Day 1	Day 2	Day 3	Day 4
3-4/100-30-3-4	173	571				
3-4/100-35-3-4	241	297				
3-4/100-40-3-4	299	308				
3-4/100-45-3-4	367	764				
3-4/102-50-3-4	181	525				
3-4/102-60-3-4	243	477				
3-4/64-45-3-4	816	1068				
3-4/64-50-3-4	870	1326				
3-4/64-55-3-4	798	1308				
3-4/64-60-3-4	960	1278				
3-4/64-65-3-4	1116	1284				
3-4/64-70-3-4	1020	1344	Car	Car	Bicycle	Car
3-4/64-75-3-4	966	1344	Car	Car	Car	
3-4/64-80-3-4	1104	1344	Bicycle	PT	Car	Car
3-4/66-125-3-4	1425	1680	PT	PT	Car	PT
3-4/66-130-3-4	1410	1680	Car	Car	PT	PT
3-4/66-40-3-4	570	1230				
3-4/66-45-3-4	590	1275				
3-4/66-50-3-4	685	1365				
3-4/66-55-3-4	825	1375				
3-4/66-60-3-4	730	1380				
3-4/T1-65-3-4	240	285	Car	Car	Car	Car
3-4/T1-70-3-4	260	285	Car	Car	Car	Car
3-4/T1-73-3-4	265	285	Car	Car	Car	Car
3-4/T1-75-3-4	270	285	PT	Car	Car	Car
3-4/T1-80-3-4	280	285	Car	Car	PT	Car
3-4/T1-85-3-4	285	285	Car	Car	Car	Car
3-4/T3-100-3-4	800	800	Car	Car	Car	Car
3-4/T3-105-3-4	730	800	Car	Car	Car	Car
3-4/T3-65-3-4	610	800	Car	Car	Car	Scooter
3-4/T3-75-3-4	610	800	Car	Car	Car	Scooter
3-4/T3-80-3-4	710	800	Car	Scooter	Car	Car
3-4/T3-85-3-4	740	800	Car	Bicycle	Car	Car
3-4/T3-90-3-4	769	800	Car	Car	Car	Car
3-4/T3-95-3-4	790	800	Car	Car	Car	Car

Table 14: The results of SET1 3-4, when there are no modes of transportation given the program was terminated before an optimal solution was found.

E Results with cost of €0.001

The following three tables show the results of SET1 with a cost of €0.001 for a gram emission of CO_2.

Instances	Initial Obj	New obj	Day 1	Day 2
1-2/100-30-1-2	173	430		
1-2/100-35-1-2	241	236		
1-2/100-40-1-2	299	319		
1-2/100-45-1-2	367	28		
1-2/102-50-1-2	155	32		
1-2/102-60-1-2	243	32		
1-2/64-45-1-2	816	778		
1-2/64-50-1-2	882	1103		
1-2/64-55-1-2	978	1342	Scooter	Scooter
1-2/64-60-1-2	1062	1343	Bicycle	Scooter
1-2/64-65-1-2	1116	1342		
1-2/64-70-1-2	1170	1343	Bicycle	Scooter
1-2/64-75-1-2	1236	1343	Bicycle	Scooter
1-2/64-80-1-2	1248	1343	Bicycle	Scooter
1-2/66-125-1-2	1635	1678		
1-2/66-130-1-2	1615	1610		
1-2/66-40-1-2	510	1572		
1-2/66-45-1-2	645	1661	Car	Car
1-2/66-50-1-2	675	1643		
1-2/66-55-1-2	635	1513		
1-2/66-60-1-2	780	1653		
1-2/T1-65-1-2	240	284	Bicycle	Scooter
1-2/T1-70-1-2	260	284	Bicycle	Scooter
1-2/T1-73-1-2	265	284	Bicycle	Scooter
1-2/T1-75-1-2	270	284	Bicycle	Scooter
1-2/T1-80-1-2	280	284	Bicycle	Scooter
1-2/T1-85-1-2	285	285	Bicycle	Bicycle
1-2/T3-100-1-2	800	800	Bicycle	Bicycle
1-2/T3-105-1-2	800	800	Bicycle	Bicycle
1-2/T3-65-1-2	610			
1-2/T3-75-1-2	670	799	Bicycle	Scooter
1-2/T3-80-1-2	710	799	Bicycle	Scooter
1-2/T3-85-1-2	740	799	Bicycle	Scooter
1-2/T3-90-1-2	770	799	Bicycle	Scooter
1-2/T3-95-1-2	790	799	Bicycle	Scooter

Table 15: The results of SET1 1-2, when there are no modes of transportation given the program was terminated before an optimal solution was found.

Instances	**Initial Obj**	**New obj**	**Day 1**	**Day 2**	**Day 3**
2-3/100-30-2-3	173				
2-3/100-35-2-3	241				
2-3/100-40-2-3	299				
2-3/100-45-2-3	367				
2-3/102-50-2-3	181				
2-3/102-60-2-3	243				
2-3/64-45-2-3	816	1235			
2-3/64-50-2-3	858	1324			
2-3/64-55-2-3	972	1339			
2-3/64-60-2-3	1062	1324			
2-3/64-65-2-3	1116	1336			
2-3/64-70-2-3	1170	1341			
2-3/64-75-2-3	1206	1325			
2-3/64-80-2-3	1284	1339			
2-3/66-125-2-3	1555	1679			
2-3/66-130-2-3	1375	1615			
2-3/66-40-2-3	570	1413			
2-3/66-45-2-3	620	1442			
2-3/66-50-2-3	675	1531			
2-3/66-55-2-3	825	1619			
2-3/66-60-2-3	635	1650			
2-3/T1-65-2-3	240	284			
2-3/T1-70-2-3	260	284	Bicycle	Bicycle	Scooter
2-3/T1-73-2-3	265	284	Bicycle	Bicycle	Scooter
2-3/T1-75-2-3	270	284	Bicycle	Bicycle	Scooter
2-3/T1-80-2-3	280	285	Bicycle	Bicycle	Scooter
2-3/T1-85-2-3	285	285	Bicycle	Bicycle	Bicycle
2-3/T3-100-2-3	800	800	Bicycle	Bicycle	Bicycle
2-3/T3-105-2-3	790	800	Bicycle	Bicycle	Bicycle
2-3/T3-65-2-3	610	799			
2-3/T3-75-2-3	670	799	Scooter	Bicycle	Bicycle
2-3/T3-80-2-3	710	799			
2-3/T3-85-2-3	740	799	Bicycle	Bicycle	Scooter
2-3/T3-90-2-3	770	799			
2-3/T3-95-2-3	790	799			

Table 16: The results of SET1 2-3, when there are no modes of transportation given the program was terminated before an optimal solution was found.

Instances	Initial Obj	New obj	Day 1	Day 2	Day 3	Day 4
3-4/100-30-3-4	173	575				
3-4/100-35-3-4	241	508				
3-4/100-40-3-4	299	288				
3-4/100-45-3-4	367	793				
3-4/102-50-3-4	181	546				
3-4/102-60-3-4	243	419				
3-4/64-45-3-4	816	1218				
3-4/64-50-3-4	870	1290				
3-4/64-55-3-4	798	1145				
3-4/64-60-3-4	960	1241				
3-4/64-65-3-4	1116	1265				
3-4/64-70-3-4	1020	1307				
3-4/64-75-3-4	966	1319				
3-4/64-80-3-4	1104	1292				
3-4/66-125-3-4	1425	1652				
3-4/66-130-3-4	1410	1678				
3-4/66-40-3-4	570	1362				
3-4/66-45-3-4	590	1510				
3-4/66-50-3-4	685	1584				
3-4/66-55-3-4	825	1561				
3-4/66-60-3-4	730	1443				
3-4/T1-65-3-4	240	284				
3-4/T1-70-3-4	260	285	Bicycle	Bicycle	Bicycle	Scooter
3-4/T1-73-3-4	265	285				
3-4/T1-75-3-4	270	284				
3-4/T1-80-3-4	280	285	Bicycle	Bicycle	Bicycle	Scooter
3-4/T1-85-3-4	285	284				
3-4/T3-100-3-4	800	800	Bicycle	Bicycle	Bicycle	Bicycle
3-4/T3-105-3-4	730	799				
3-4/T3-65-3-4	610	798				
3-4/T3-75-3-4	610	799				
3-4/T3-80-3-4	710	799				
3-4/T3-85-3-4	740	795				
3-4/T3-90-3-4	769	799				
3-4/T3-95-3-4	790	799				

Table 17: The results of SET1 3-4, when there are no modes of transportation given the program was terminated before an optimal solution was found.

F Results with cost of €0.01

The following three tables show the results of SET1 with a cost of €0.01 for a gram emission of CO_2.

Instances	Initial Obj	New obj	Day 1	Day 2
1-2/100-30-1-2	173	536,8428956		
1-2/100-35-1-2	241	467,9033223		
1-2/100-40-1-2	299	619,9169869		
1-2/100-45-1-2	367	648,0049875		
1-2/102-50-1-2	155	331		
1-2/102-60-1-2	243	391		
1-2/64-45-1-2	816	1328,754189	Scooter	Scooter
1-2/64-50-1-2	882	1.328		
1-2/64-55-1-2	978	1.329	Scooter	Scooter
1-2/64-60-1-2	1062	1334,043348	Bicycle	Scooter
1-2/64-65-1-2	1116	1320,429006		
1-2/64-70-1-2	1170	1.327		
1-2/64-75-1-2	1236	1334,905429		
1-2/64-80-1-2	1254	1.335		
1-2/66-125-1-2	1630	1.662		
1-2/66-130-1-2	1600	1.666		
1-2/66-40-1-2	495	1.423		
1-2/66-45-1-2	645	1.469		
1-2/66-50-1-2	545	1.497		
1-2/66-55-1-2	635	1.531		
1-2/66-60-1-2	760	1643,952195		
1-2/T1-65-1-2	240	276,5976399	Bicycle	Scooter
1-2/T1-70-1-2	260	277,2113981	Bicycle	Scooter
1-2/T1-73-1-2	265	277,4988466	Bicycle	Scooter
1-2/T1-75-1-2	270	277,5829217	Bicycle	Scooter
1-2/T1-80-1-2	280	280	Bicycle	Bicycle
1-2/T1-85-1-2	285	285	Bicycle	Bicycle
1-2/T3-100-1-2	800	800	Bicycle	Bicycle
1-2/T3-105-1-2	800	800	Bicycle	Bicycle
1-2/T3-65-1-2	610	783,4966723		
1-2/T3-75-1-2	670	790,0131398	Bicycle	Scooter
1-2/T3-80-1-2	710	790,153674	Bicycle	Scooter
1-2/T3-85-1-2	740	791,0949704	Bicycle	Scooter
1-2/T3-90-1-2	770	791,2494306	Bicycle	Scooter
1-2/T3-95-1-2	790	791,6744306	Bicycle	Scooter

Table 18: The results of SET1 1-2, when there are no modes of transportation given the program was terminated before an optimal solution was found.