Influence of Topology and Payload on CO_2 Optimised Vehicle Routing

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Abstract. This paper investigates the influence of gradient and payload correction factors used within a CO_2 emission model on the solutions to shortest path and travelling salesman problems when applied to freight delivery.

Problem instances based on real life examples using the road network of Scotland are studied. Solutions are obtained using a range of metrics and vehicles. The results are compared to determine if the inclusion of gradient and payload as inputs to the emission model have any influence on the final routes taken by vehicles or the order of visiting customers. For the problem instances studied no significant influence was found. However for vehicle routing problems with large differences in payload and hilly road networks further investigation is needed.

1 Introduction

The routing and scheduling of vehicles is a well researched topic and one that has many practical applications. The efficient routing of freight delivery, waste collection, courier services and road gritting are examples.

Typically the objective function to be optimised is related to the number of vehicles used, the distance travelled or to an overall cost. Optimising routing and scheduling problems with respect to CO_2 emissions has, until recently, received little attention.

The Intergovernmental Panel on Climate Change (IPCC) concludes that the main source of increased CO_2 levels in the atmosphere are a result of the burning of fossil fuels [2]. A number of international treaties to control greenhouse gases have been agreed. These incude the United Nations Framework Convention on Climate Change [3] and the Kyoto Protocol to the Framework Convention on Climate Change [4]. The Climate Change Act 2008 legally committed the UK government to reduce CO_2 emissions by at least 26% from the 1990 levels by 2020 [5]. Road freight transport accounted for 6% of all UK CO_2 emissions in 2004 [6].

In this paper we explore some of the factors that influence road vehicle optimisation problems, particularly with respect to the minimisation of CO_2 emissions from the transport of goods. In particular the effect of road gradient and vehicle payload are examined as these factors have been shown to have a considerable impact on the level of fuel consumed and thus CO_2 emitted.

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2 Related Work

The traveling salesman problem and the Vehicle Routing Problem (VRP) have been well studied. A survey of methods for solving the Traveling Salesman Problem can be found in Lawler et al. [10]. A review of the application of evolutionary algorithms to the TSP can be found in [12].

However only a few studies have been done with regard to CO_2 emissions. Sbihi and Eglese [13] reviewed the link between vehicle routing problems and green logistics. Palmer [14] integrated an emissions model with a genetic algorithm to minimise CO_2 emissions for supermarket home deliveries. This study utilised a light goods vehicle for which the fuel consumption is not influenced by payload and road gradient.

The effect of payload and gradient on optimum route choice has been studied by [15] [16] on the mountainous Cape Verde isles in the context of a waste collection service. These effects are most noticeable for long distance transportation when the vehicle is fully laden with waste. Fuel savings of 52% were achieved when optimising the route for low fuel consumption rather than distance.

Ericsson, Larsson and Brundell-Freij [17] developed a routing tool for drivers that minimised fuel consumption.

In [18] Jabali et al. optimised a time dependent vehicle routing problem for both total travel time and total CO_2 emissions. A simple average speed CO_2 model was used and payload and gradient were ignored.

3 CO_2 Emission Modelling

This study employed the COPERT [9] model which is based on the average speed of a vehicle and includes payload and correction factors for heavy goods vehicles (HGVs). Payload and gradient do not have a significant impact on the fuel consumption and emissions from light goods vehicles. Although mainly used to calculate the annual emissions of a country's vehicle fleet, the methodology used within COPERT has been shown to be sufficiently accurate to calculate emissions with a temporal resolution of 1 hour and a spatial resolution of 1 km. The use made of this model within this study falls outside these bounds. Other models exist [8] that would permit a much smaller spatial and temporal resolution. However these models require more data inputs and involve more complex processing than the model selected. In addition these models were not available to the authors at the time of writing.

The COPERT model models both cold start and hot engine emissions. In this study only hot engine emissions were considered.

For this study several vehicle classifications were used. These are a light goods vehicle (LGV) and 7.5 tonne, 18 tonne and 26 tonne rigid-bodied heavy goods vehicles (HGVs). All were assumed to have engines conforming to the most recent engine standards, that is Euro 6 for the LGV and EuroVI for HGVs.

The output from the COPERT model is a baseline emission factor giving the grams of CO_2 emitted per kilometre. The emission factor is a function of the vehicle classification, the European emission standard of the engine and the mean speed of the vehicle. CO_2 emissions are directly proportional to fuel consumption.

For HGVs a gradient correction factor is then applied to this emission factor to correct for uphill and downhill slopes. The gradient correction factor is a function of the vehicle mass, the mean vehicle speed and the road gradient. The baseline emission factor is corrected as follows:

$$\eta_i = G_i e_i \ . \tag{1}$$

where

η_i is the gradient corrected emission factor in g CO_2/km of vehicle i, G_i is the gradient correction factor of vehicle i and e_i is the baseline emission factor of vehicle i.

The above emission factors assume that the vehicle is 50% loaded. To compensate for different vehicle loadings the emission factor for HGVs can be corrected as follows:

$$\beta_i = \eta_i[1 + 2\lambda_i(L - 50)/100] \ . \tag{2}$$

where

β_i is the load corrected emission factor in g CO_2/km of vehicle i, η_i is the gradient corrected emission factor of vehicle i, λ_i is the load correction factor of vehicle i and L is the actual loading of vehicle as a percentage of the maximum load.

The final emission factor is then used to calculate the cost of traversing a given road link as follows:

$$cost_{i,j} = \beta_{i,j} l_j \ . \tag{3}$$

where

$cost_{i,j}$ is the cost in g CO_2 of vehicle i traversing roadlink j, $\beta_{i,j}$ is the load corrected emission factor of vehicle i on roadlink j and l_j is the length of roadlink j in km.

4 Experimental Approach

The study is based on two very different sets of problem data. The first concerns the delivery of groceries to households within the City of Edinburgh from a supermarket store. The second concerns the delivery of paper from a warehouse in North Lanarkshire to commercial customers throughout Scotland. In the first instance a diesel-fuelled light goods vehicle (LGV) was studied. In the second instance a variety of rigid-bodied heavy goods vehicles (HGVs) and LGVs are employed.

The mapping data employed for this study is from the UK Ordnance Survey's (OS) Integrated Transport Network (ITN) layer with the Ordnance Survey's Land-Form PROFILE providing height data. This mapping data was loaded into a MySQL database. The map for Scotland includes approximately 500,000 nodes and 600,000 edges. The study only included deliveries within mainland Scotland and no use of ferries or railways was made.

There is no information on vehicle speeds in the OS ITN data. While the ITN data does contain basic information about road categories, the assignment of an appropriate vehicle speed is far from simple. For example a road category of 'A Road' can represent both a rural road with a legal speed limit of 60mph or a city centre street with a legal limit of 30mph.

Land-Use and Transport Integration in Scotland (LATIS)[20] models road transport on the strategic road network in Scotland. LATIS takes into account land-use planning and travel demand and can be used to predict the congested average speed of traffic on all roads in the model, as well as the free-flow speed. Thus the LATIS model can supplement the OS data providing vehicle speed data for a subset of the roads. For roads outside the LATIS model only estimates based on the limited OS road categories can be used. The estimates for this study are based on measurements made by the Department of Transport [19] and are shown in table 1.

The vehicle speeds employed in this paper are an initial estimate only. They do not consider the effect of congestion, the varying of congestion with time or driver choice of speed. These will be studied in future work.

Table 1. Default average speeds for road categories not in the LATIS model

ITN Road category	speed km/h
Single carriageway	45
A Road	45
B Road	45
Minor road	45
Local street	45
Pedestrianised street	30
Alley	30

Several traveling salesman problem (TSP) instances were randomly chosen from the problem datasets. Each of these represented a typical route for that vehicle type in an operational solution to the problem data. As the loadings of the vehicles were often far less than the maximum, the delivery quantities to the customers was increased so that the vehicle typically left the depot 80-100% fully laden. This does not apply to LGVs where the payload has no effect on the fuel emission factor. The number of deliveries ranged from 5 to 13. Details are diplayed in table 2.

A bidirectional form of Dijkstra's routing algorithm [7] was used to find the shortest paths between all pairwise combinations of customers and the depot. The following objectives were used;-

- Least Distance.
- Least CO_2 emissions without the payload and gradient correction factors.

Table 2. Problem instances studied

Problem	Number of deliveries	Vehicle	%laden	Average distance (km)
1	10	LGV Diesel	n/a	9.6
2	5	7.5t rigid HGV	81	115.3
3	6	18t rigid HGV	80	132.8
4	13	26t rigid HGV	93	102.2

- Least CO_2 emissions with gradient correction factor.
- Least CO_2 emissions with the gradient and payload correction factors.

These objective functions are hereafter referred to with the following names;-

- Distance
- CO_2(basic)
- CO_2(gradient)
- CO_2(gradient/payload)

The COPERT model has gradient correction factors for slopes between -6% and 6%. Where an edge was found that had a slope outside of this range the nearest corresponding factor was employed.

The Distance and CO_2(basic)shortest paths are symmetrical, whereas taking the gradient into account makes the shortest paths asymmetrical. That is the cost of travelling from A to B is not necessarily the same as travelling from B to A. Likewise the optimal route may also be different. When calculating the shortest paths for the CO_2(gradient/payload) objective the process was repeated for vehicle loadings of 0, 50 and 100% to find out if the loading of a vehicle affected the optimal route between 2 points.

Although the shortest paths were constructed to minimise the above objective functions they were all costed and analysed using the full CO_2 model that is using both gradient and payload correction factors. For each of the 3 CO_2 objective functions the shortest paths found were compared with the corresponding paths found for the distance objective. The CO_2 savings for each path and the additional distances travelled to acheive that saving were then analysed.

The TSP instances were then solved for each of the objective functions using the appropriate shortest paths as inputs. Since it is the input factors to the emission model that are being studied, the choice of TSP algorithm is not the focus of this paper, therefore, the smaller instances were solved by iterating through all solution possibilities. The larger instances were solved using an evolutionary algorithm proposed by [11]. The best solution found in each case is reported.

When optimising using the CO_2(gradient/payload) objective function three paths between each pair of customers or customer/depot have been calculated. These paths are the optimal path for a 0, 50 or 100% laden vehicle and may or may not be different. The path chosen depends on the current loading of the vehicle which, in turn, depends on the customer's position in the overall TSP route. Vehicle with loading of 25% or less were assigned to the 0% laden path, those with loading of 75% or greater the 100% laden path and the rest the 50% laden path.

As before the calculated TSP solutions were also costed and analysed using the full CO_2 model with both gradient and correction factors. This calculation also took into account the current loading of the vehicle that was updated as the vehicle completed its tour of customers.

5 Evidence

The results of all the shortest path calculations are displayed in figures 1 and 2.

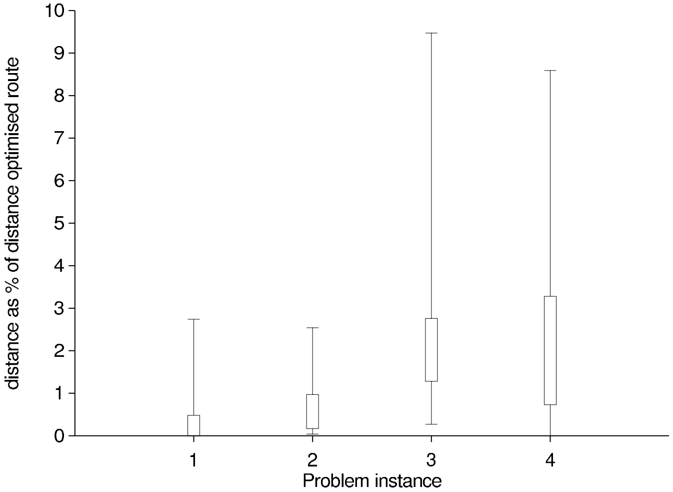

Fig. 1. Extra distance of CO_2 optimised paths for all pairwise combinations of customers and depot compared with distance optimised paths. The box represents the 2nd and 3rd quartiles and the whiskers give the minimum and maximum values.

These show that, for the problem instances chosen, CO_2 savings for any one path of up to 23% are possible. However the CO_2 savings are highly dependent on the problem instance. For example problem instance 1 is based on grocery home deliveries in Edinburgh and for many pairs of customers the distance and CO_2 optimised paths are identical. The average saving is 0.5%. Problem instance 2 is based on paper deliveries from Lanarkshire, Scotland to customers in Edinburgh, Glasgow, Fort William, Angus and West Lothian. CO_2 savings ranged from 3.21% to 23.77% with an average of 12.47%. This difference in CO_2 savings is to be expected as the distances involved are much longer and there is more potential for alternative paths.

T-Tests were undertaken to compare the CO_2 savings of the CO_2(basic) objective function and the CO_2(gradient) function against the distance objective. Similarly the CO_2 savings of fully-laden and empty vehicles using the CO_2(gradient/payload) objective function against the distance objectie were

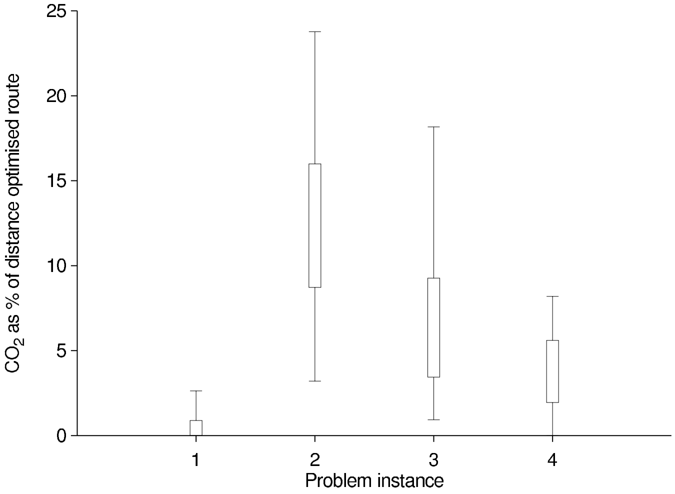

Fig. 2. CO_2 savings of CO_2 optimised paths for all pairwise combinations of customers and depot compared with distance optimised paths. The box represents the 2nd and 3rd quartiles and the whiskers give the minimum and maximum values.

compared. The t-test results are display in tables 3 and 4. These show that taking the gradient of a road into account or not when searching for a shortest path does not make a significant difference to the distance travelled or the CO_2 saved. Similarly shortest paths for empty and fully-laden vehicles are not significantly different.

Table 3. T-Test to compare the differences between CO_2 optimised paths and distance optimised paths with the differences between CO_2(gradient) optimised paths and distance optimised paths

Problem	Extra distance	CO2 saving
2	1.00	1.00
3	0.95	0.87
4	0.81	0.72

The results of the TSP solutions are compared in table 5. As for the shortest paths the level of CO_2 savings possible is dependent on the problem instance. The additional distance necessary to achieve reductions in CO_2 is not high. In addition the solutions were examined to check the order that customers are served. For problem instances 1, 2 and 3 there was no difference in the delivery order for any of the metrics. Thus the CO_2 savings come from different paths between customers rather than a different TSP solution.

For problem 4, however, the ordering of customers does vary. The CO_2(basic) optimised TSP solution visits customers in the same order as that of the distance

Table 4. T-Test to compare the differences between CO_2 optimised paths with 0% payload and distance optimised paths with the differences between CO_2 optimised paths with 100% payload and distance optimised paths

Problem	Extra distance	CO2 saving
2	0.99	1.00
3	0.98	0.99
4	1.00	1.00

Table 5. Extra distance travelled and CO2 savings achieved by CO2 optimised TSP solutions when compared with distance optimised solutions

Vehicle	Problem	Metric	Distance (km)	CO2 (g)	Extra distance	CO2 saving
LGV Diesel	1	Distance	70495	12225		
LGV Diesel	1	CO2	70748	12112	0.36%	-0.92%
18t HGV	2	Distance	557130	284806		
18t HGV	2	CO2	558259	246556	0.20%	-13.43%
18t HGV	2	CO2/gradient	558156	246553	0.18%	-13.43%
18t HGV	2	CO2/gradient/payload	558156	246553	0.18%	-13.43%
7.5t HGV	3	Distance	769328	209889		
7.5t HGV	3	CO2	787610	195818	2.38%	-6.70%
7.5t HGV	3	CO2/gradient	787600	195816	2.38%	-6.70%
7.5t HGV	3	CO2/gradient/payload	787621	195821	2.38%	-6.70%
26t HGV	4	Distance	835894	434228		
26t HGV	4	CO2	849199	426456	1.59%	-1.79%
26t HGV	4	CO2/gradient	850045	424761	1.69%	-2.18%
26t HGV	4	CO2/gradient/payload	852130	426099	1.94%	-1.87%

optimised solution. The CO_2(gradient) optimised solution shows a slight variation in order whilst the CO_2(gradient/payload) has a further customer order. However, although the solutions in terms of order of delivery are different, the overall difference in the CO_2 emission levels is very small.

6 Conclusions

The potential for CO_2 savings and the influence of gradient and vehicle payload on vehicle routing solutions are highly dependent on the problems studied. For the problem instances considered in this paper a wide range of potential CO_2 savings was found for both shortest path and traveling salesman problems. Even in problems where there are alternative paths between two customers with a large potential CO_2 saving this does not always lead to a difference in the final TSP solution in terms of a different order of visiting customers. In these cases the CO_2 savings arise from different paths between customers rather than a different order. Gradient and payload were found to effect the TSP order solution in one problem instance. However the difference in CO_2 emissions between the solutions is less than the 2.1% coefficient of variation of the COPERT model for CO_2 as reported in [21].

In this study considerable computing effort and time was spent in calculating the paths between customers, especially when taking the vehicle payload into account. This was due to the size of the mapping data rather than the size of the TSP problem. Further work is needed to examine the algorithm used to calculate the inputs for a CO_2 optimised TSP to reduce the pre-processing effort needed.

In this study the effect of time windows, congestion and the opportunity for a driver to select an optimal vehicle speed were ignored. Future work will examine the effect of these on potential CO_2 emissions.

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