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Model proposals for the optimization and calculation of the environmental impact of municipal solid waste collection routes

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Abstract. In the context of municipal solid waste collection, with the aim to obtain a sustainable service, the present work aims to provide some models for calculating the CO2eq emitted by a fleet of vehicles. The existing literature about vehicle emissions and the bi-objective routing problem were analysed. Results adaptable to the scenario of municipal solid waste collection were searched and then applied to a software of management systems of waste collection previously developed. The research carried out shows how it is possible to calculate, for different scales of detail, the punctual emissions of the collection service, and optimize them, applying the criterion of least environmental impact to a routing algorithm.

1. Introduction

Municipal solid waste (MSW) collection is an issue that affect the overall waste management system, the organization of specific areas like the touristic ones involving expertise that require enhanced skills, all under circular and sustainable concepts [1-13]. The issue of environmental impact is part of the municipal solid waste collection service [14-18]. Developing routing algorithms aimed at reducing emissions from collection vehicles or being able to estimate the amount of CO2eq emitted by the service are necessary measures to optimize the service and calculate the increasingly requested environmental impact indices [19-22]. This research aims to valorize the literature on the topic of routing for the minimization of CO2eq emissions to apply it to a specific waste collection system; in this case, door-to-door collection, street container and ODS (On-line Demand Service). The objective is to be able to calculate emissions in a timely manner (e.g., collection route) using the data available from the fleet management and navigation application software, in this case one developed by I&S in the frame of a research project [23]. Indeed, results can be more accurate than the only use of emission factors and total kilometres travelled. This target is coherent with the requests of recent calls for tender that are characterizing the sector of waste collection in regions with an enhanced waste management.

2. Methodology

The environmental impact of the collection service is almost entirely due to the movement of vehicles; therefore, the authors tried to find emission calculation methodologies that are as precise and reliable as possible. A methodology to calculate the environmental impact in terms of CO2eq of the collection service, with the level of detail of the individual scheduled routes was considered for the development of the calculations. Some methods can be used depending on the level of detail of the desired result and depending on the quality of the data available. The emissions of a vehicle depend on a multitude of factors such as the fuel used, the type of vehicle (total mass), the driving style, the traffic conditions, etc. [24-29]. To deal with this complexity of factors, simplified but still reliable formulations for calculating emissions were sought. In particular, expressions studied in the literature that quantify CO2eq emissions as a function of the speed of the vehicle were analyzed. The results are useful in order to obtain important statistics on the collection service with a view to reducing emissions. Considering the I&S technologies [23], a review of the main scientific articles in this field was carried out to be able to find a methodology that can be implemented on I&S applications.

3. Results and discussion

The result of this paper is an approach for calculation of CO2eq of existing MSW collection scheduled routes. Quantifying the environmental impact in terms of CO2eq of MSW collection and more in detail of a door-to-door system in the perspective of reducing emissions is one of the main goals of this research.

3.1. *Simplified approach based on emission factors.*

There are several studies regarding the calculation of fuel consumption (therefore of CO2eq emissions through emission factors -EF) but none of these were proposed and applied to a specific context such as a MSW door to door collection [30-32]. The complexity imposed by this type of MSW collection includes the repeated stops and restarts of the vehicle which make it difficult to quantify fuel consumption accurately based exclusively on the emission factors that can be found in the literature; many of these, in fact, are based on average and constant speeds (DEFRA, EEA) [33-34]. An article that implements the calculation of fuel consumption in road congestion contexts is [35], which states that, in real “start and stop” conditions, up to 40% more is emitted compared to a “steady state” scenario at constant speed. The emission index provided by [33] is an information per unit of distance travelled. The Pollution-Routing Problem and the minimization of the distance travelled in the context of the Vehicle Routing Problem – VRP, does not necessarily coincide with the minimization of fuel consumption and therefore of emissions as reported in [30]. Using only the data of the kilometres travelled in a collection route to calculate the CO2eq emitted may therefore be unreliable. The methods illustrated below for the calculation of the environmental impact do not use engine data detectable in real time but still provide results as realistic as possible going beyond the simple counting of the kilometres travelled. Some of these proposed methods will be applicable in the case where the vehicle speed data detected in real time by control units installed on board the vehicles is available. In fact, fuel consumption does not depend only on the distance travelled

Activity	Type	0% Laden	50% Laden	100% Laden	Average laden
		kg CO2e/km	kg CO2e/km	kg CO2e/km	kg CO2e/km
HGV (all diesel)	Rigid (>3.5 - 7.5 tonnes)	0.45221	0.49106	0.52991	0.48562
	Rigid (>7.5 tonnes-17 tonnes)	0.54088	0.6172	0.69352	0.59277
	Rigid (>17 tonnes)	0.7468	0.90836	1.06991	0.97436
	All rigids	0.65828	0.78306	0.90784	0.82313

Table 1. DEFRA emission factors per unit of kilometre for HGV's [36]

but also on other factors such as the type of road section considered (Table 4) and the slope and the driving style (bi-objective Pollution-Routing Problem).

A useful dataset is the emission coefficient provided by EEA [34] (Table 2), calculated with the "tier 1" method, the simplest, but the only one of the three methods that provides the emission index for CO2eq. The other methods (tier 2 and tier 3), although more precise, focus exclusively on other combustion products in which CO2 is excluded.

Subsector units	Fuel	kgCO2 per kg of fuel[1]
All vehicle types	Diesel	3.169
	LPG[2]	3.024
	CNG[3] (or LNG)	2.743

[1] CO2 emission factors are based on an assumed 100% oxidation of the fuel carbon (ultimate CO2).

[2] LPG assumed to be 50% propane + 50% butane.

[3] CNG and LNG are assumed to be 100% methane

Table 2. CO2 emission factor per unit of fuel consumed provided by "tier 1" method of calculation of GHG emissions of European Environment Agency

The data provided by EEA needs to be multiplied by the density of the fuel and by conversion parameters to obtain an emission in terms of kgCO2eq/Lfuel. We obtain a value of 2.69 (for diesel, in line with the index provided by DEFRA as can be seen in Table 3). This data provides the emission index per litre of fuel consumed; it will therefore be necessary to obtain the specific data of fuel consumption, whether it is measured directly by the control unit installed on board or obtained through indirect expressions based on the velocity of the vehicle (also measurable by a control unit installed).

Fuel	Unit	kg CO2e
Diesel (100% mineral diesel)	tonnes	3203.91
	litres	2.66
	kWh (Net CV)	0.27
	kWh (Gross CV)	0.25

Table 3. DEFRA index of emission of CO2eq per unit of fuel consumed (Diesel)

The punctual velocity measurement has already been implemented since more a decade [37], while the fuel measurement has not yet been implemented due to greater operational difficulties. In the absence of the punctual velocity measurement, we can refer to an average value depending on the road class (Table 4). Each road segment can therefore be associated with its typology as an additional attribute to the GIS layer [38].

The calculation of emissions can be obtained by multiplying the fuel consumption factor in Table 4 by the emissions conversion factor of 2.66 from DEFRA, Table 3 (or 2.69 from EEA), and by the length of the road section considered. The total impact will finally be given by the sum of the contributions of each individual road section travelled.

Road Classes	Fuel Consumption [g/km]
Urban	225
Rural	150
Highway	165

Table 4. COPERT III index of emission of heavy duty vehicles depending on road morphology

3.2. *Emission calculation on network arcs by using the mean velocity.*

An alternative to using the fuel consumption factor reported in table 2 is to use the vehicle speed/velocity. For a simplified approach, an average travel speed can be associated with each type of road (table 1) and the environmental impact can be calculated using expressions that link average speed with emissions/fuel consumption. The authors of the research [32] proposes the equation 1. This equation directly relates the average speed of the vehicle to emissions. In Table 5, the parameter corresponding to the vehicle type that are most used in *municipal solid waste* collection are reported.

$$\varepsilon = K + av + bv^2 + cv^3 + \frac{d}{v} + \frac{e}{v^2} + \frac{f}{v^3} \quad (1)$$

Where:

ε: rate of emission in g/km for an unloaded goods vehicle, on road with a gradient of 0%
K: is a constant
$a - f$: are coefficients
v: is the mean velocity of the vehicle in km/h

	K	***a***	***b***	***c***	***d***	***e***	***f***
3.5-7.5 t	110	0	0	0.000375	8702	0	0
7.5-16 t	871	-16	0.143	0	0	32031	0

Table 5. Coefficients of emission functions for heavy goods vehicles vs gross vehicle weights

The authors of the research [30,31] propose the expression developed by the well-known COPERT method for calculating fuel consumption [36]. The calculation of fuel consumption must be performed for each road section. The data regarding the speeds is shown in Table 6, and refers to the average reference speeds for the type of road in the considered road section.

Pollutant	Weight class	Speed range [km/h]	Emission factor [g/km]
Fuel Consumption	Weight<7,5t	0 - 47	$1425,2V^{-0,7593}$
		47 - 100	$0,0082V^{2}$ - 0,0430V + 60,12
	7,5<Weight<16t	0 - 59	$1068,4V^{-0,4905}$
		59 - 100	$0,0126V^{2}$ - 0,6589V + 141,18
	16<Weight<32t	0 - 59	$1595,1V^{-0,4744}$
		59 - 100	$0,0382V^{2}$ - 5,1630V + 399,3
	Weight>32t	0 - 58	$1855,7V^{-0,4367}$
		58 - 100	0,0765V2 - 11,414V + 720,9

Table 6. Speed dependency of emission and consumption factors for diesel heavy duty vehicles

These average travel speeds can be obtained from a statistical analysis of the GPS data of the vehicles during the collection routes in order to have typical speed values for each area. Further developments of regards the introduction of corrective factors to fuel consumption based on the percentage of load transported and based on the slope of the road section (in the absence of the load correction factor, the expression refers to 50% filling). The main equations (2)-(5) for these factors are then shown below in equation (2)-(5).

$$fc = FCS * LCF * GrCF \tag{2}$$

fc: Total fuel consumption factor

$$LCF = 1 + 0.36 * \frac{(LP - 50)}{100} \tag{3}$$

LCF: Load Consumption Factor
LP: Load Percentage

$$GrCF = 0.41 * e^{0.18x} \tag{4}$$

GrCF: Gradient Consumption Factor
x: slope

$$FC_k = \sum\nolimits_{i=1}^{n} Lseg_i * fc_i \tag{5}$$

n: total amount of road arcs
Lseg: Length of i-th arc

This research was carried out in the context of municipal solid waste collection and involves the inclusion of some parameters such as the slope of the road arcs (incorporating the elevation) into the road network layer) and the vehicle load percentage. In equation (2) the factor FCS (Fuel Consumption) indicates the fuel consumption and it can be calculated using the data from Table 5, according to the type of vehicle and the velocity regime of the road arc considered.

A further formulation that relates speed to fuel consumption is given by researchers [39,40] which inserts into the equations some parameters specific to the vehicle type; below are reported the main equation (6)-(7). The parameters used in the expressions are reported in Table 6 and refer to a diesel vehicle for the transport of medium-sized goods.

$$FR = \lambda(kN_eV + \gamma(\beta v^3 + \alpha(\mu + f)v)) \tag{6}$$

$$F = \lambda(kN_eV * \frac{d}{v} + \gamma\beta dv^2 + \gamma\alpha(\mu + f)d) \tag{7}$$

Where

F: Total amount of fuel used to travel a distance d(m) at constant speed v(m/s) with load *f*(kg). *F* is obtained multiplying equation (6) by “d/v” which is the time of traveling.
FR: Istantaneous fuel use rate (l/s)
Ψ: Conversion factor from (g/s) to (l/s)

$$\alpha = gsin\phi + gC_rcos\phi \tag{8}$$

$$\beta = 0.5 * C_dA\rho \tag{9}$$

$$\gamma = 1/(1000\varepsilon\varpi) \tag{10}$$

$$\lambda = \xi/\kappa\Psi \tag{11}$$

To apply this last formulation, it is necessary to have the technical data of each type of vehicle present in the fleet to obtain accurate results (Table 7). All these formulations involve the calculation of the fuel consumption (and therefore the emissions) for each individual road arc included in the collection route, to which an average travel speed is associated. These average travel speeds can be obtained by doing a statistical analysis of the historical data having the GPS readings available, or by arbitrarily assigning a speed value depending on the classification (Table 4).

Notation	Description	Value
ξ	Fuel-to-air mass ratio	1
κ	Heating value of a typical diesel fuel (kJ/g)	44
Ψ	Conversion factor (g/l)	737
k	Engine friction factor (kJ/rev/l)	0.2
Ne	Engine speed (rev/s)	33
V	Engine displacement (l)	5
ρ	Air density (kg/m3)	1.2041
A	Frontal surface area (m2)	3.912
μ	Curb-weight (kg)	6350
g	Gravitational constant (m/s2)	9.81
ϕ	Road angle	0
Cd	Coefficient of aerodynamic drag	0.7
Cr	Coefficient of rolling resistance	0.01
ε	Vehicle drive train efficiency	0.4
ϖ	Efficiency parameter for diesel engines	0.9

Table 7. Vehicle and emissions parameter

4. Conclusions and further implementations

The formulations proposed in this paper, considering the scientific research in this area, allow to calculate the environmental impact associated with the travel of a certain road arc whose obtainable results are certainly more accurate than the only use of emission factors and total kilometres travelled. A possible implementation of the proposed “model” is to exploit the same expressions for the calculation of emissions seen in the previous section, using as input not an average speed but a specific speed measured by control units installed in the vehicles. In some cases, like the one managed by I&S, control units can transmit data with a minimum time interval in the order of tens of seconds. In this way, the fuel consumption and therefore the calculated emissions would reflect reality in a timely manner. The calculation in this way is disconnected from the road arcs but calculated with a precision in the order of a meter. The possibility of transmitting data with this level of detail allows to take into greater account the accelerations and braking due to traffic conditions in real time.

There could be some criticalities: one depends on the velocity of data elaboration due to the high flux of data sent by the device; the other one is related with the possible to link the slope of the arcs to the GIS layer used. The slope in facts needs to be calculated by integrating the elevation at the nodes of each arc.

An interesting implementation is not to limit at calculating the emissions of collection routes, but apply a routing algorithm for route planning, as a criterion, considering the cost of emissions, as well as the distance travelled. Currently, the VROOM algorithm (Vehicle Routing Open-source Optimization Machine [41]) is used as a route planner. Route optimization occurs by minimizing an objective function that is currently the total distance.

The solution with a shorter travel distance does not always imply the minimization of emissions [42], therefore it is possible to define a different objective function, aimed at minimizing emissions. The researchers [30, 31] have developed a simple but effective approach to the problem. A 3D GIS model is applied for the analysis of road networks where the elevation of the DTM for each node of the network has been linked to the road network layer. In this way, each segment is associated with a constant slope. Finally, for each arch, an associated emission factor is calculated, using equations (2)-(5). The attributes of each road arc are length, slope and FC (fuel consumption factor). To calculate this factor, the study refers to an average travel speed attributed to the type of road segment (table 1). The final objective function to be minimized will therefore be the sum of this coupled parameters: emission factors and the length of the arcs.

Routing algorithms are well suited for optimizing so-called "by objective" collection routes where the input is a discrete series of points (collection spot, on-demand services) where good route planning can lead to real savings of time and CO_2 emissions. It must be verified whether this advantage can also be obtained by extending the algorithm to plan MSW door-to-door collection routes. In this case, the points entered as input are much greater (corresponding to each individual user) and the discretion in choosing possible route alternatives is reduced to a minimum since all the road arcs in the chosen area must be served.

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