

A SOFTWARE TOOL FOR ACCURATE ASSESSMENT OF COSTS AND CO₂ EMISSIONS IN WOOD TRANSPORT USING OpenStreetMap[©]

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ABSTRACT. Costs and environmental impacts are key elements in forest logistics and they must be integrated in forest decision-making. The evaluation of transportation fuel costs and carbon emissions depend on spatial and non-spatial data but in many cases the former type of data are difficult to obtain. On the other hand, the availability of software tools to evaluate transportation fuel consumption as well as costs and emissions of carbon dioxide is limited. We developed a software tool that combines two empirically validated models of truck transportation using Digital Elevation Model (DEM) data and an open spatial data tool, specifically OpenStreetMap[©]. The tool generates tabular data and spatial outputs (maps) with information regarding fuel consumption, cost and CO₂ emissions for four types of trucks. It also generates maps of the distribution of transport performance indicators (relation between beeline and real road distances). These outputs can be easily included in forest decision-making support systems. Finally, in this work we applied the tool in a particular case of forest logistics in north-eastern Portugal.

Keywords: Forest logistics, transportation, biomass, road analysis, Open Geographical Data.

1 INTRODUCTION

The use of openly accessible geographic databases can be a simple and effective solution in the development of forestry applications requiring spatial data. These databases provide ways of overcoming the lack of exact data and information that still affects many regions in the world. This is particularly pertinent at fine scales, where tools to support decision-making and planning in forestry in the context of global economic competitiveness, such as optimization tools, are urgently needed. The optimization of time and resources are of major importance in increasing economic benefits in forestry or in determining the limits of viability for forest products and services. As in other fields, distance and travel time are essential factors in forest management and planning since they are directly related to transportation costs and economic viability [13, 22]. Additionally, distance and travel time are directly related to CO₂ emissions of forest activities, particularly under current climatic change mitigation efforts pushed by the society in general and the forest sector in particular.

At present there are numerous available geographic open source tools for use in management applications [30, 34], but geographic information is often too difficult or too expensive to obtain. There are, however, geographic databases that offer openly large amounts of geospatial data under different themes. The free accessible geographic databases with higher potential for routing optimization are i) Google Maps, from Google Inc. ii) Bing, from Microsoft Corporation, and iii) OpenStreetMap[©], supported by the OpenStreetMap Foundation. OpenStreetMap[©] is developed and maintained by a community of volunteers where each user provides new data and data updates at very short intervals [11, 15, 16]. Data is released under an Open Data Commons Open Database License (ODbL).

Generally, there are two ways to access data from these databases. One way is by calling a web API (Application Programming Interface) and the other by downloading static database files. This latter form is only available in OpenStreetMap[©] among all the aforementioned sources. The simplicity of queries and the fact that it doesn't require local computation, since all processing is done remotely, are the major strengths of API. However, restric-

tions on the number of queries allowed by the server, in order to prevent fraudulent access, decrease the efficiency of the process which limits the use of API. In the case of static maps, there are no restrictions of queries since calls are done locally making this their major strength. Static maps, nevertheless, require large local data storage capacity and involve more complex developing code. When one application runs a small number of queries (e.g., when conducting transport assessments based on a low number of routes) it is recommendable to use API queries but when the number of queries is high (e.g., when the number of routes is high), the use of static geographical databases is usually preferable.

Examples of using web geographical databases found in the literature include the improvement of quality of global land cover maps using Google Earth images and a global network of volunteers [12], the development of a volunteered geographic information system to analyze urban energy efficiency using a Google Maps API [1], the supply of farmers and anthropologists with spatial information using Google Earth images [20], the establishment of a decision support system for traffic management with routing API of Google Maps [27], and the development of hydrological and hydraulic models based on OpenStreetMap[®] data [28].

Costs in logistics are key elements in forestry [8, 26, 33]. Currently, the logistics costs in biomass supply chains are more relevant because they are more dependent on the rising price of fossil fuels thus, affecting directly, in many cases, costs of collection and transportation. Distance and travel costs optimization related issues have been explored in the scientific literature for the biomass supply chain involving harvesting, collecting, assortments, storage, and transport [6]. Available studies include evaluation of harvesting costs based on spatial resource distributions (e.g., [19]) and evaluation of costs in long-distance (international) movements of biomass (e.g., [23, 29]). Routing optimization in particular has received attention not just from an economical perspective but also from an environmental point of view given the relationship between transportation distances and fossil fuel derived carbon dioxide [9, 17]. For example, in Portugal a theoretical straight radius of 35 km was applied around wood-fired power plants for determining the optimal zone for collecting wood based on linear programming models [31] and in Spain a radius of 50 km was applied for 2MW electric power plants [26]. Other works introduce the logistics costs factor as a restriction in linear programming problems to minimize transport distance (e.g., [14]).

The North-east of Portugal is a region with a large forest cover component, occupying nearly 30% of its area, mainly maritime pine (*Pinus pinaster* Ait.), Pyrenean oak (*Quercus pyrenaica* Willd.) and sweet chestnut (*Castanea sativa* Mill.). In general, the forest character of

the region is not reflected in terms of forestry activity or forest related businesses. Sweet chestnut, managed in agroforestry systems, centers attentions from producers and markets due to the high value of chestnuts and the high incomes it generates locally. These are open systems (usually from 70 to 160 trees/ha) aiming to maximize fruit production involving fertilization and irrigation, in particular in years after establishment. The production of chestnut can be combined with other activities such as animal production based on pastureland, mushrooms picking, and game. The remaining forest systems in the area, however, lack management objectives and initiatives, as well as tools to support management. The inexistence of management raises concerns at several levels such as the potential increase in fire hazard, decrease in wood quality, and accelerated human depopulation of rural areas. More than 7200 fires have occurred in the past 10 years in the region, affecting more than 12,000 ha of forest land and 49,000 ha of scrubland [18].

Valorization of forests in the region through planning, enhancement of silvicultural treatments such as pruning, thinning, or regeneration of stands, or through the development of new forest products markets [3] requires minimizing transport costs thereof [32]. Tools for the assessment of costs in the geographical context of this region are, however, currently not available.

The region nowadays needs biomass production for energy purposes, even in cities. For example, in Bragança, the largest city in the region, nearly 50% of households use firewood for heating [4]. Wood pellets are an emergent industry in Portugal and it is still growing. According to the Portuguese National Association of Biomass Energy Pellets the annual production in 2012 was at the level of 700,000 ton with expectations to overcome 1 million ton year⁻¹ at the end of 2013 [2]. The volume of annual sales is around 100 million Euro [2]. The production is mostly exported but the internal consumption, which is 10 to 12% of the production, is rising quickly. Near 80% of the actual pellets production is based on maritime pine (*Pinus pinaster* Ait.) [2]. The national market of biomass for energy has suffered a substantial change in the last years. Traditionally, firewood and wood briquettes were used in manual feeding equipment. The development of a national pellet producing industry, together with an increasing search of viable alternatives to replace fossil fuels created the condition for the penetration of higher efficiency pellet burners in the market [10]. Although producing annually reasonable amounts of forest biomass, there are not currently pellets plants located in the region. Thus, a first approximation to address the possible use of wood biomass from the Nordeste region in wood pellets production should be to analyze the feasibility of the nearest production plant as a final destination of this biomass taking into account transport costs based on the

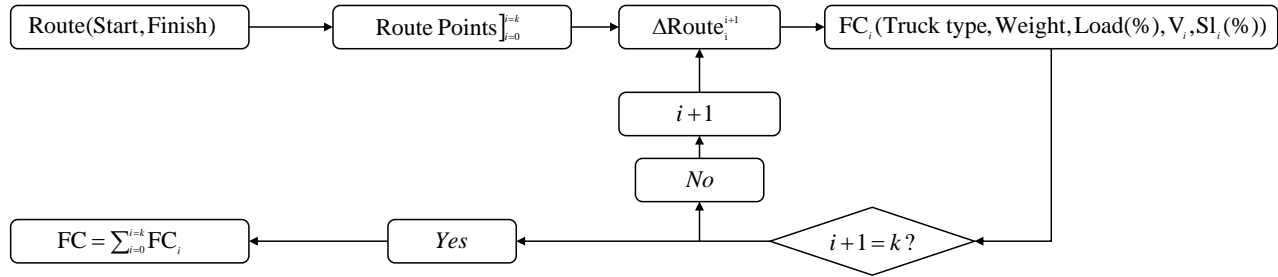


Figure 1: General scheme of fuel consumption (FC) calculation for a particular route. V_i : Average velocity in section i ; Average slope in section i .

physiographic characteristics of the area as well as the road infrastructure.

Under the conditions presented above, the main objective of this study was to create an open software tool based on publicly accessible geographical data to assess biomass transportation fuel consumption, costs, and CO₂ emissions. It is also an objective of this study to test the tool under realistic scenarios, namely the transportation of biomass for a pellets production plant located outside of the study area.

2 METHODOLOGY

2.1 General approach The method we developed is based on a set of variables that we considered as fundamental to support a logistics model adjusted to any specific region. These include variables that are independent of spatial data and variables that require spatial data to be calculated.

In general terms, a logistics route is defined by a starting point (e.g., a forest industry for which biomass is destined) and an ending point (e.g., a forest where wood is collected). The location of each point is defined by its coordinates (latitude and longitude). In forestry, for one particular fixed starting point there is usually a large set of possible ending points in a region (e.g., all harvestable forest stands). An entire region must therefore be evaluated for each end point considered in the analysis. All regions have a set of potential points to define one route. Every starting point defines a set of coordinates for the truck travel to start. The ending points are set as a grid. An entire region is defined by the coordinates of two corners of the grid: lat_{max} , lat_{min} , $long_{max}$, $long_{min}$. When a grid is defined by a matrix of (x, y) points, the coordinates of ending points are automatized (Supplementary Material A1).

For each ending point there is an optimal route (solved by OsmSharp.dll for a specific vehicle) to a starting point (this last is fixed) (Supplementary Material A2). Due to the large number of queries involved, the geographic data used is obtained from

OpenStreetMap[©] through downloading static databases from OpenStreetMap[©] Data Extracts [Available at: <http://download.geofabrik.de/index.html>]. The files extension are “pbf”, and the OsmSharp.dll has a specific instance to read this kind of file types using the directives OsmSharp.Osm.PBF.Streams and OsmSharp.Routing.Osm.Interpreter to input the data in the system.

Each route is a set (0, 1, . . . , k) of geographic points denoted by (Route points) k_0 , and each pair of consecutive points define a section (Δ^{i+1}_i Route). Each section has its properties and characteristics that affect fuel consumption (FC) calculation. Total fuel consumption of a specific route is calculated as the summation of consumption in all sections from start to finish (Figure 1).

2.2 Fuel consumption calculation Fuel Consumption (FC) is directly related with i) Truck type, ii) Weight (truck + load), iii) Load proportion, iv) Truck speed, and v) Terrain slope [7] (see Supplementary Material B). For an individual transport from a starting point to an ending point, it can be assumed that truck type and weight are constant but speed and slope vary according to the specific conditions in each of the sections of the A – B route where the truck is at a particular moment (Equation 1) [7].

$$FC = f(\text{Truck type, Weight, Load } \%, V_i, Sl_i) \quad (1)$$

Where:

$$\begin{aligned} FC &= \text{Fuel consumption (g/km),} \\ V_i &= \text{Average velocity in section } i(\text{km/h),} \\ Sl_i &= \text{Average slope in section } i(\%). \end{aligned}$$

From the FC base calculation it is possible to obtain associated Fuel costs (Equation 2) and CO₂ emissions (Equation 3).

$$F_{cost} = FC / (1000 \cdot DC) \cdot d_i \cdot P \quad (2)$$

Where:

Table 1: Characteristics of different truck types considered in the tool for estimating fuel consumption and costs, and CO₂ emissions of road transport in the Nordeste Transmontano region, Portugal.

Truck Type	Weight (tonne) category	Weight (tonne) (Load 0%)	Weight (tonne) (Load 100%)	Load (tonne)	Width (m)	Length (m)
I (Rigid Small)	≤ 14	5	12	7	2.3	8
II (Rigid Big)	> 14	10	28	18	2.3	12
III (Articulated Small)	≤ 32	12	26	14	2.4	12
IV (Articulated Big)	> 32	20	45	25	2.5	16

F_{cost} = Fuel cost (€),
 FC= Fuel Consumption function (see Supplementary Material B),
 DC = Fuel density (g/l),
 d_i = Length of section *i* (m),
 P= Fuel Price (€/l).

$$E_{CO_2} = FC \cdot C \cdot d_i \quad (3)$$

Where *C* = 3.16 is the Diesel-CO₂ emission conversion factor [7].

2.3 Variables determination

2.3.1 Geographic data independent variables

Truck type and load percentage are defined independently of geographic data. There are different kinds of trucks with different weights, lengths, and load characteristics. In this work we choose the more representative truck types used in forest biomass transportation in Portugal (Table 1).

The efficiency of using logistics resources is essential. For this reason, during transportation, trucks can travel completely filled (Load = 100%) in any of the routes. However, due to the particular characteristics of transport of wood it is possible that trucks travel empty (Load = 0%). Additionally, in some conditions it might be advantageous that trucks transport half of their capacity (Load = 50%).

2.3.2 Geographic data dependent variables

A set of variables in the model requires geographic data to be derived from. In the following sections we describe how these variables are calculated.

Slope factor (Sl_i) The slope of a $\Delta Route_{i+1}^i$ is defined as the relative difference in elevation between points *i* and *i*+1 divided by the distance between them (Equa-

tion 4).

$$Sl_i = (Elev_{i+1} - Elev_i) / d_i \cdot 100 \quad (4)$$

Where:

Elev_{*i*} and Elev_{*i*+1} = Elevation of points *i* and *i*+1, respectively (m),
 d_{*i*} = Horizontal length of section *i* (m).

The information included in static maps of OpenStreetMap[®] provided the latitude and longitude of all the points of an optimal route. Since elevation data is not part of this database, we used the Digital Elevation Model (DEM 30m Portugal WGS84, available in <http://www.arcgis.com>) in raster format for a matrix defined by location parameters similar to those used for the region (lat_{max}, lat_{min}, long_{max}, long_{min}). The elevation matrix data and the slope function calculation process is shown in Supplementary Material A3. Data is loaded in ASCII raster format. Number of rows and columns and resolution data are shown in the heading of the file.

Velocity Factor (V_{*i*}): The factor velocity is the most complex variable in terms of calculation since it takes many factors into account. The velocity in a given section is determined by the minimum of three possible velocities (Equation 5): i) maximal legal, ii) maximal for the curve in terms of safety, and iii) velocity that the truck is able to achieve.

$$V_i = Min(V_a, V_b, V_c) \quad (5)$$

Where:

V_{*a*} = Max legal velocity (km/h),
 V_{*b*} = Max velocity for pass the curves with safety (km/h),
 V_{*c*} = Estimation of velocity in section by Kinematic truck Model (km/h),
 V_{*i*} = Estimated velocity in section *i* (km/h).

Max legal velocity (V_a) OpenStreetMap[©] provides data containing Maximal legal velocity for each point of the optimal route, associated to each point by elements called tags. Max legal velocity data is obtained by two options: i) “HighwayType” tag (this option is automatized according to the process described in Supplementary Material A4 where each “HighwayType” is associated to a generic maximal velocity (Decree-Law n^o44/2005 of 23 February of Portugal) for each kind of road) and ii) “MaxSpeed” tag (this option does not appear in all cases, but when it does it is set as default for the max velocity).

As in Supplementary Material A4, there is the possibility of defining several values for the Coefficient of friction (μ) parameter for each possible road type. In this work, we considered μ as a constant and equal to 0.5 [24].

Maximum safe velocity (V_b) The maximum velocity allowed for each road section was defined as equal to the force of the weight of the truck (F) and the centripetal force (F_c) in the basal range for a maximal safety range (Figure 2). The two forces are combined in V_b (Equation 6) and in Supplementary Material A5.

$$V_b = \sqrt{((W_i/4)/(h/2)) \cdot g \cdot \mu \cdot R} \quad (6)$$

Where:

- V_b = Maximum safe velocity,
- W_i = The width of the truck,
- h = The height of the truck,
- g = Gravity force,
- μ = Coefficient of friction of the road,
- R = The ratio of the curve.

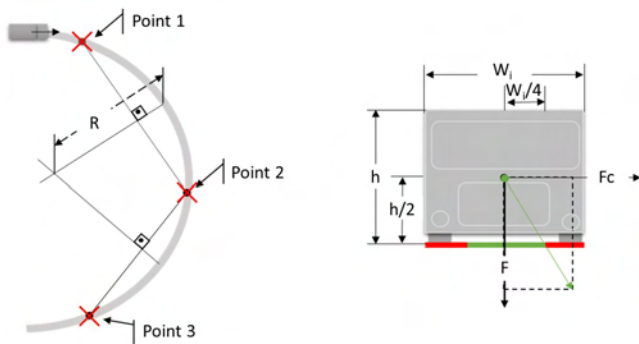


Figure 2: Representation of the method to estimate the ratio of a curvature (R) between three consecutive points and the scheme of forces that affect the stability of a truck in a curve. The vector resulting from summing truck weight and centripetal forces determines if the truck can role or not. In this case the safety range falls into $W_i/4$ for each side of the truck.

The coefficient μ depends on the particular type of road under consideration but since data on this attribute is not provided by OSM it is not possible to establish this parameter. For that reason we assumed μ constant and equal to 0.5 [24].

Velocity in section (V_c): kinematic truck model

Truck speed at a particular instant in time is affected by various factors. In this study we considered only objective factors not taking into account subjective factors, such as experience or expertise of the driver, to simplify the process. We started from elementary physics according to which velocity at a certain instant i is equal to the initial velocity plus the acceleration in an instant i during time t (Equation 7).

$$V_{c_i} = V_{c_{i-1}} + a_i \cdot t \quad (7)$$

Where:

- $V_{c_{i-1}}$ = Initial velocity in section
- a_i = Instant acceleration,
- t = Time.

Velocity depends essentially on instant acceleration (a_i) at a particular time. To obtain this acceleration we used a kinematic application for truck movement [24, 25], as described in Equation 8.

$$a_i = (F_i - R_i)/W \quad (8)$$

Where:

- F_i = Forces favorable to forward movement (N) at an instant i ,
- R_i = Resistance forces (N) at an instant i ,
- W = Total mass of the truck (kg).

Acceleration is the difference between the forces that make the truck to advance (F) minus the reactive forces of the progression (R) [24] (Equation 9 and Equation 10).

$$F = \min(F_t, F_{\max}) \quad (9)$$

Where:

- F_t = Tractive effort (N) which depends on i) the power of the truck, ii) the velocity at the time of calculation and iii) the efficiency in transmitting force,
- F_{\max} = Maximum tractive force (N): which depends on i) the vehicle mass on tractive axle or axles and ii) friction coefficient (μ).

$$R = R_a + R_r + R_g \quad (10)$$

Where:

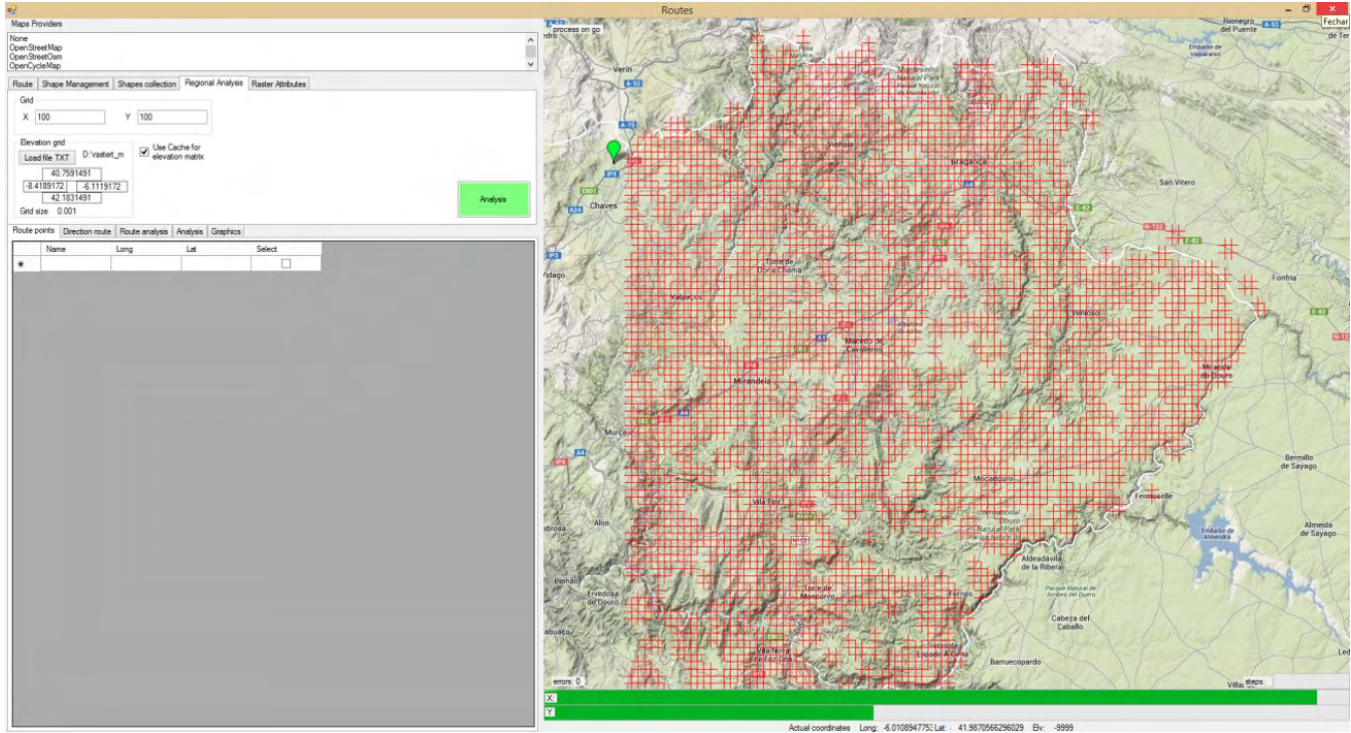


Figure 3: Main form of the application developed for estimating consumption, costs, and emissions of road transport in the Nordeste Transmontano region, Portugal.

Ra = Aerodynamic Resistance (N) which depends on i) truck frontal area, ii) truck speed, iii) truck drag coefficient, and iv) altitude coefficient,
 Rr = Rolling resistance (N) which depends on i) total truck mass, ii) rolling coefficient, and iii) rolling resistance coefficients,
 Rg = Slope resistance (N) which depends on i) total truck mass and ii) slope (%).

To obtain a_i , Rakha et al. [24] used increments of time (Δt) to recalculate a_i as a function of time. In this work we solved the same system but with increments of distance (Δd) because it is more operational in our model (Equation 11, Supplementary Material A6).

$$a_{di} = (F_{di} - R_{di})/W \quad (11)$$

Where: $di = d_0 + \Delta d$

$$\begin{cases} \dot{v}(di) \\ \dot{x}(di) \end{cases} = \begin{cases} a(di) \\ v(di) \end{cases}$$

$$\begin{cases} Vc_i = Vc_{i-1} + a_i \cdot t \\ x_i = x_{i-1} + V_i \cdot t \end{cases}$$

2.4 Tool The pseudo code described in this paper can be compiled in different program languages. We developed an application form in C# language using

Visual Studio 2013 express (Microsoft Corporation) and the OsmSharp.dll (Figure 3) for applying the processes and methodology described above (see the main classes and procedures at Supplementary Material C). The interface of the application allows the user to define the area of analysis to be considered, the starting point and the ending grid points (x, y).

3 APPLICATION

We applied our tool in a real case scenario to analyse the efficiency and viability of road transport of resources with low value such as wood biomass. The particular objective of this application was to quantify costs, fuel consumption and CO₂ emissions by truck type and fuel price in road transport of forest biomass from an entire region to a single destination (starting point): a pellets production plant located outside the study region. We wanted also to generate cost and CO₂ emissions spatial surfaces for the study area to be used as criteria in a forest decision support system.

3.1 Study area Our study was conducted in the most northeastern part of Portugal (Nordeste Transmontano). With a total surface of 527,705 ha, the Nordeste Transmontano encompasses eight municipalities (Afanedega da Fé, Bragança, Vimioso, Vinhais, Mogadouro, Miranda

Table 2: Additional parameters for different truck types considered in the tool for estimating fuel consumption and costs, and CO₂ emissions of road transport in the Nordeste Transmontano region, Portugal. “T. efficiency” is the coefficient of transmission efficiency; “A” is the truck frontal area (m²); “Cd” is the truck drag coefficient (%).

Truck type	Tractive axle (%)	Engine power (kW)	T. efficiency (%)	A (m ²)	Cd (%)
I - Rigid small	67	186	89	6.8	70
II - Rigid large	8	246	89	6.8	70
III - Articulated small	31	335	89	10	70
IV - Articulated large	43.5	410	89	10.7	70

Table 3: General results of Fuel Consumption and CO₂ emissions for routes evaluated in the Nordeste Transmontano region, Portugal, by truck type analyzed.

		Type I	Type II	Type III	Type IV
Consumption	Average (l/km)	0.225	0.3	0.296	0.373
	Max (l/km)	0.244	0.329	0.325	0.411
	Min (l/km)	0.199	0.261	0.255	0.305
	Standard deviation (l/km)	0.005	0.008	0.008	0.011
Emissions	Average (g/km)	590.183	786.55	776.384	977.112
	Max (g/km)	639.9	862.689	851.609	1076.969
	Min (g/km)	522.064	683.996	669.95	799.458
	Standard deviation (g/km)	13.413	20.497	20.976	29.655

do Douro, Mirandela, and Macedo dos Cavaleiros). Total forest area in the region is 284,946 ha [5].

3.2 Inputs The tool was applied considering two types of trucks, rigid and articulated, and two size categories, small and big (Supplementary Material C).

The application was run under the following conditions (inputs):

- Region delimitation:
 - Long_{max} = -7.4185806640.
 - Long_{min} = -6.1262890625.
 - Lat_{max} = 42.02073285264.
 - Lat_{min} = 40.96745587327.
- Grid size: x = 100, y = 100.
- Destination coordinates (starting point):
 - End_{lat} = 41.801519.
 - End_{long} = -7.452455.
- A run cycle consisted of a round trip from starting point (A) to ending point (B) with a load of 0% and return from ending point (B) to starting point (A) with load of 100%. In both cases (A-B and B-A) the optimal route was resolved independently, since road conditions and legal directions might change.
- Pick up sites (ending points) are stop places where trucks load wood; they exclude Motorways or in

Residential areas because wood loading would not be possible in these sites

- Additional truck parameters are shown in Table 2.

3.3 Results The application of the software tool under the conditions of the study area in the Northeast of Portugal allowed the estimation of a number of indicators of interest for the evaluation of transport of wood from any place in the region to a pellets industry located at the border of this area. The use of a 100 x 100 grid in the study region constrained by the destination coordinates returned 3,868 routes to potential collection points. Of these, only 3,107 satisfied the restriction of destination is a pick up site, since 761 fell in residential areas or motorways and are not suitable for wood loading.

Using only routes satisfying the criteria above, the application allowed extracting output data in tabular format concerning optimal distances, costs, and emissions, as well as maps representing the distribution of output simple and composite variables. The general results for fuel consumption and CO₂ emissions according to the type of truck that can operate in the region are shown in Table 3.

With the data of each route we created maps for consumption and CO₂ emissions for each truck type using the Natural Neighbour function of ArcGIS[®] (see Figure 4 and Figure 5 for fuel consumption and CO₂ emissions,

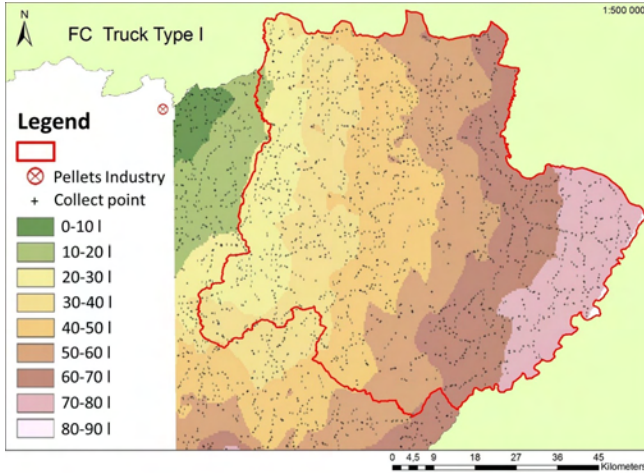


Figure 4: Fuel Consumption for truck type I (Rigid small) for the Nordeste Transmontano region, Portugal, in relation to a starting point corresponding to a wood pellets plant.

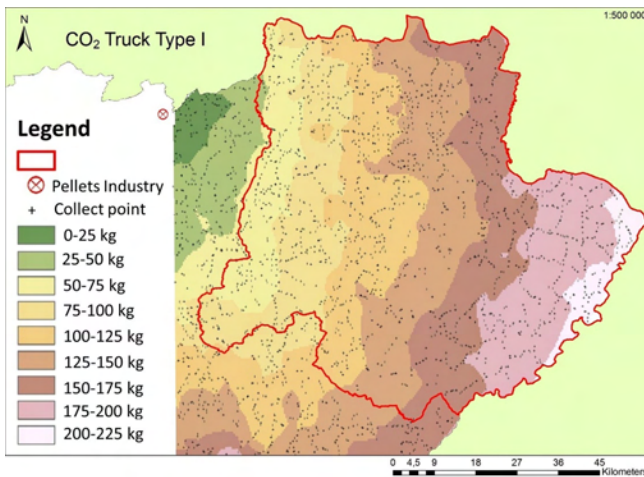


Figure 5: CO₂ emissions for truck type I (Rigid small) for the Nordeste Transmontano region, Portugal, in relation to a starting point corresponding to a wood pellets plant.

respectively, for truck type I). Maps for the remaining truck types (Fig. 7) are presented as supplementary material (Supplementary Material D).

The cost of transport depends directly on fuel price. Due to the high variability of diesel prices we analyzed the cost of consumption for different diesel prices in general for the region (Table 4). The average costs are representative of the entire region because they result from a large number of road types and different topography conditions in the region for the four truck types used in the simulations.

Estimates of distances can also be derived for each route and presented in absolute or relative terms thus providing additional information on transport efficiency

Table 4: General unitary cost per kilometer derived from fuel consumption data for four types of trucks in the Nordeste Transmontano region, Portugal.

		Diesel price (€/l)			
		1.1	1.2	1.3	1.4
Average cost (€/km)	Type I	0.248	0.330	0.326	0.410
	Type II	0.270	0.360	0.355	0.447
	Type III	0.293	0.390	0.385	0.484
	Type IV	0.315	0.420	0.414	0.522

Table 5: Ratios of relation between routes from A to B (A-B) and B to A (B-A) with the beeline A-B in a simple direction (Ratio A-B:Beeline and Ratio B-A:Beeline respectively) and from A to B to A with two times the beeline A-B (Ratio A-B-A:2Beeline) for the road system in the Nordeste Transmontano region, Portugal. A is the starting point (a wood pellets plant) and B are all collection points in the region. STD denotes standard deviation.

	Ratio		
	Ratio A-B: Beeline	Ratio B-A: Beeline	Ratio A-B-A: 2Beeline
Average	1.6206	1.6235	1.6221
Max	2.2867	2.2909	2.2888
Min	1.2383	1.2289	1.2336
STD	0.1232	0.12	0.1212

and performance. In Table 5 and Figure 6, we present the average of the ratio between the road distance between starting point (A) and ending point (B) (both ways) and from point A to B and return, and the corresponding beeline distance (A and B).

4 DISCUSSION

Assessments of fuel consumption in forest logistics are often based on average consumption or standard factors per km of travel applied to average distances (e.g., [21], [23], [29], [31]). This kind of assessments can be applied at a large scale, but often it does not represent well real local conditions; thus, it creates wood transport cost estimates that might diverge from actual costs. The software tool developed here, on the contrary, takes into consideration particular local conditions at a very detailed scale, such as slopes, road type, and accurate locations of pick up site, thus providing accurate estimates of costs, as well as of fuel consumption and CO₂ emissions. This detailed assessment results for accurate and detailed data provided by OpenStreetMap[©] data, including the route calculation library (OsmSharp.dll) used to estab-

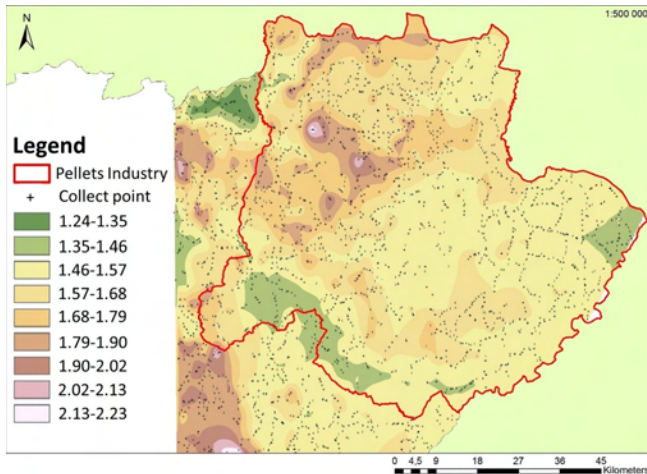


Figure 6: Geographical data of Ratio (A-B-A: 2 Beeline) for the Nordeste Transmontano region in relation to a starting point corresponding to a wood pellets plant.

lish routes between points. The Open Source Data of OpenStreetMap[©] is constantly updated by community of volunteers revising periodically data which allows the periodic updating of the logistics indicators estimated by the software tool we developed. All inputs in the tool can be modified and it is possible to evaluate additional scenarios such as winter weather conditions, new types of vehicles and different velocity limits (for example for emergency vehicles).

In the case study of the Nordeste region, the application of the tool produced useful information to support forest management decision-making. For example, it is possible from the outputs to locate sites for wood collection with transportation costs below a certain threshold established based on biomass prices at the destination (e.g., 30€/ton in Portugal). The same can be done for carbon dioxide. The results of the application of the tool can also support the definition and implementation of measures to minimize fuel consumption and thus CO₂ emissions in forest logistics in the region. This can be achieved through selection of routes and areas where consumption was observed to be lower in relation to other routes or areas or where observed levels of consumption or emission were below a certain target value. In this regard, the tool can also be used to test the effects of changing not just physical aspects of the roads and the road network (pavement, design, etc.) but also vehicle technology (engine, tires, etc.) or human variables (driver experience) in fuel consumption and emissions.

The software tool we developed will produce information on logistics variables such as transport costs and CO₂ emissions to be used as criteria in forest decision-making in the Nordeste Transmontano region with the purpose of optimizing the location of wood pellets plants

in the region, evaluating the economic viability of routing and industry destinations, and evaluating different alternatives in future road expansion.

5 CONCLUSIONS

In this work a software tool was developed to assess key determinants of forest logistics, in particular costs and CO₂ emissions related to road transport. The tool uses different types of data (spatial and non-spatial) and has the flexibility to be adapted to the characteristics of any particular region. In the tool development, two empirical validated methodologies were used: the dynamics model for maximum truck acceleration and the model of fuel consumption. It also combines the two creating a truck simulator applied to real surface spatial attributes. OpenStreetMap[©] is a reliable open source of geographical information, constantly maintained and updated and offering many capabilities to the user. The OpenStreetMap[©] offers the possibility of providing the statics maps that can be used in automatic routines using a large number of queries, like in our application. The tool and the development methodology proposed here can help to analyze spatial movement or resources taking into account different factors of particular regions such as road typology, truck types, topology, etc., to evaluate and map fuel consumption, costs and CO₂, offering the possibility of taking these results into account in forest decision-making. The results of the application of our tool are important and very useful in providing spatial and numerical information that can be used in forest logistics in a given area to detect problems and to look for solutions to minimize costs and CO₂ emissions, but there are many other possible applications.

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A SUPPLEMENTARY MATERIAL: PSEUDO CODES

A1: Pseudo code to automatize coordinates of ending points **using** a grid in a delimited region.

```
Using: OSMSSharp
Procedure: Region
Input: Coordinate Longmin, Latmin Longmax Latmax
For (int i = 0; i <= a; i++)
    For (int j = 0; j <= b; j++)
        end_lon = (Longmin) + (Math.Abs(Longmin - Longmax) / a) * i;
        end_lat = (Latmin) + ((Latmin - Latmax) / b) * j;
        start = new PointLatLng(starlat, starlong);
        end = new PointLatLng(endlat, endlong);
    End for
End for
Return: PointLatLng start
End procedure: Region
```

A2: Pseudo code **for** route optimization between two coordinates **using** OsmSharp.Osm.PBF.Streams;

```
using OsmSharp.Routing;
using OsmSharp.Routing.Osm.Interpreter;
Procedure: OptimalRoute
Input: Coordinate start_Lat, start_Lng, end_Lat, end_Lng
var resolved1 = router.Resolve(Vehicle.BigTruck, new
OsmSharp.Math.Geo.GeoCoordinate(start_Lat, start_Lng));
var resolved2 = router.Resolve(Vehicle.BigTruck, new
OsmSharp.Math.Geo.GeoCoordinate(end_Lat, end_Lng));
// calculate route.
var route = router.Calculate(Vehicle.BigTruck, resolved1, resolved2);
Return route;
End procedure
```

A3: Pseudo code **for** slope estimation between two points **using** a specific DEM in ASCII format.

```
Using: OSMSSharp
Procedure: Region
Input: Coordinate Longmin, Latmin Longmax Latmax
For (int i = 0; i <= a; i++)
    For (int j = 0; j <= b; j++)
        end_lon = (Longmin) + (Math.Abs(Longmin - Longmax) / a) * i;
        end_lat = (Latmin) + ((Latmin - Latmax) / b) * j;
        start = new PointLatLng(starlat, starlong);
        end = new PointLatLng(endlat, endlong);
    End for
End for
Return: PointLatLng start
End procedure: Region
```

A4: Pseudo code **for** the establishment of legal velocity **using** the OpenStreetMap Data "HighwayType" tag.

```
Procedure: MaxLegalVelocity
Input: HighwayType Hype
Double Va = 0;
```

```

if (HighwayType == "motorway") -> Va = 100; }
if (HighwayType == "trunk") -> Va = 80; }
if (HighwayType == "primary") -> Va = 80; }
if (HighwayType == "secondary") -> Va = 70; }
if (HighwayType == "tertiary") -> Va = 70; }
if (HighwayType == "unclassified") -> Va = 80; }
if (HighwayType == "residential") -> Va = 40; }
if (HighwayType == "service") -> Va = 30; }
if (HighwayType == "motorway_link") -> Va = 60; }
if (HighwayType == "trunk_link") -> Va = 60; }
if (HighwayType == "primary_link") -> Va = 50; }
if (HighwayType == "secondary_link") -> Va = 50; }
if (HighwayType == "tertiary_link") -> Va = 50; }
if (HighwayType == "living_street") -> Va = 30; }
if (HighwayType == "pedestrian") -> Va = 20; }
if (HighwayType == "track") -> Va = 20;
Return Va;
End procedure: MaxLegalVelocity

```

A5: Pseudo code **for** the calculation of the ratio of curvature between two coordinates.

```

Procedure: Curvature
Input: double X1, double Y1, double X2, double Y2, double X3, double Y3
double Ratio;
double a = Math.Sqrt(Math.Pow(X1 - X2, 2) + Math.Pow(Y1 - Y2, 2)) * 100;
double b = Math.Sqrt(Math.Pow(X2 - X3, 2) + Math.Pow(Y2 - Y3, 2)) * 100;
double c = Math.Sqrt(Math.Pow(X3 - X1, 2) + Math.Pow(Y3 - Y1, 2)) * 100;
double denRatio = (Math.Sin(Math.Acos((Math.Pow(a, 2) - Math.Pow(b, 2) -
Math.Pow(c, 2)) / (-2 * b * c)))) * 2;
Return Ratio * 1000
End procedure: Curvature

```

A6: Pseudo code to estimate the velocity of a truck between two points.

```

Procedure: Vc
Input: double velocity, double distance, double weight, double mu, double
slope, double elevation, double power
For (int i = 0; i <= distance*1000; i++)
// Calculate F
double Mta; // = Define parameter Mta;
double F = 9.8066 * weight * Mta * mu;
// Calculate Ft
double Ft = 3600 * 0.89 * (power / velocity);
// Calculate Ra
double c1 = 0.047285; // is constant;
double Cd = // = Define parameter Cd;;
double Ch = 1 - 0.000085 * elevation;
double A; // = Define parameter A;
double Ra = c1 * Cd * Ch * A * Math.Pow(velocity, 2);
// Calculate Rr
double Cr; // = Define parameter Cr;
double C2; // = Define parameter C2;
double C3; // = Define parameter C3;
double Rr = 9.8066 * Cr * (C2 * velocity + C3) * weight / 1000;
// Calculate Rg

```

```

double Rg = 9.8066 * weight * slope / 100;
// Calculate R
double R = Ra + Rr + Rg;
double a = (Math.Min(F, Ft) - R) / weight;
double t = (distance/1000) / velocity;
Vci = Vci-1 + a * t;
End for
Return Vci
End procedure: Vc

```

B SUPPLEMENTARY MATERIAL — EQUATIONS APPLIED IN FUEL CONSUMPTION CALCULATION: FC (TRUCK TYPE, WEIGHT LOAD PERCENTAGE, VELOCITY, SLOPE)

Font: EMEP/EEA (2013)

Table B: Equations applied in fuel consumption calculation: FC (Truck type, Weight Load percentage, Velocity, Slope).

T. type	% slope	% load	Eq. Type1	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
I	-6	0	Eq. A	664.55823	0.9570022	-0.5134748	-	-
I	-6	50	Eq. B	-7.9777611	182.13264	5.5153746	2.0975186	-0.0089466
I	-6	100	Eq. B	-7.5394195	166.29979	5.8176705	2.1677622	-0.009613
I	-4	0	Eq. C	11.28247	-15.5865	-2.0177201	-	-
I	-4	50	Eq. C	12.056496	-19.532977	-2.2067022	-	-
I	-4	100	Eq. D	-0.0008254	0.1542265	-9.9851294	237.76994	-
I	-2	0	Eq. D	2917.7595	1.0125629	-1.1430934	-	-
I	-2	50	Eq. C	7.9292672	-2.478343	-0.9694032	-	-
I	-2	100	Eq. D	-0.0010026	0.1876354	-12.360846	332.17662	-
I	0	0	Eq. A	2028.4551	1.0146246	-0.898327	-	-
I	0	50	Eq. A	1691.0673	1.0107097	-0.7638133	-	-
I	0	100	Eq. A	1478.6155	1.0074281	-0.6540388	-	-
I	2	0	Eq. A	1443.0554	1.0126787	-0.6664953	-	-
I	2	50	Eq. A	1285.8385	1.0099298	-0.5414106	-	-
I	2	100	Eq. A	1216.0173	1.0077448	-0.4507751	-	-
I	4	0	Eq. A	1211.9379	1.01057	-0.5063448	-	-
I	4	50	Eq. A	1063.3692	1.0070366	-0.3570552	-	-
I	4	100	Eq. A	1048.9866	1.0048163	-0.2719746	-	-
I	6	0	Eq. A	1029.7032	1.0076371	-0.3587513	-	-
I	6	50	Eq. E	1488.0338	-0.684967	215.96762	0.1535674	-
I	6	100	Eq. D	-0.0024109	0.3176589	-14.466683	842.45479	-
II	-6	0	Eq. C	13.758599	-23.442671	-2.6962432	-	-
II	-6	50	Eq. B	-14.55865	311.60501	4.6595269	1.8456395	-0.0060372
II	-6	100	Eq. B	-12.621964	245.52814	5.6714483	2.0881829	-0.0084357
II	-4	0	Eq. A	1188.5325	0.9689277	-0.5159119	-	-
II	-4	50	Eq. A	759.80631	0.9621383	-0.3099059	-	-
II	-4	100	Eq. D	-0.0011814	0.2244267	-14.955974	368.97118	-
II	-2	0	Eq. C	8.2647891	-1.4857645	-0.9654162	-	-
II	-2	50	Eq. D	-0.001678	0.305809	-19.767193	518.63079	-
II	-2	100	Eq. D	-0.001599	0.2939372	-19.698191	546.27395	-
II	0	0	Eq. A	2509.1997	1.0081738	-0.7632624	-	-
II	0	50	Eq. A	2072.2285	1.004001	-0.6068544	-	-
II	0	100	Eq. A	1817.4461	1.000557	-0.4841271	-	-

II	2	0	Eq. A	2119.256	1.0092279	-0.6106017	-	-
II	2	50	Eq. A	1915.8423	1.0068375	-0.4698263	-	-
II	2	100	Eq. A	1875.3849	1.004855	-0.3764674	-	-
II	4	0	Eq. A	1945.7298	1.0088558	-0.4935859	-	-
II	4	50	Eq. A	1709.1108	1.0052248	-0.316049	-	-
II	4	100	Eq. A	1777.3794	1.0032778	-0.2336836	-	-
II	6	0	Eq. E	177.107	0.2371867	3411.2551	-0.8258885	-
II	6	50	Eq. A	1767.1442	1.0042966	-0.2379125	-	-
II	6	100	Eq. D	-0.0060042	0.7078024	-29.340175	1576.6602	-
III	-6	0	Eq. C	14.105519	-25.449992	-2.8173741	-	-
III	-6	50	Eq. B	-10.624079	228.76887	5.8694875	2.1813923	-0.0099616
III	-6	100	Eq. B	-9.5945152	193.8603	6.7541126	2.3960349	-0.0120616
III	-4	0	Eq. A	930.32642	0.9654672	-0.4465249	-	-
III	-4	50	Eq. A	594.30572	0.9595132	-0.238592	-	-
III	-4	100	Eq. D	-0.0010874	0.2067291	-13.803647	341.58295	-
III	-2	0	Eq. C	9.0051657	-5.1946817	-1.1809174	-	-
III	-2	50	Eq. D	-0.0015042	0.2759418	-18.04247	478.22576	-
III	-2	100	Eq. D	-0.0014681	0.2706602	-18.290058	512.42884	-
III	0	0	Eq. A	2478.5936	1.008829	-0.7890916	-	-
III	0	50	Eq. A	1915.303	1.0035637	-0.5944679	-	-
III	0	100	Eq. D	-0.0013695	0.2718437	-19.157568	713.75302	-
III	2	0	Eq. A	1975.4006	1.0093608	-0.603163	-	-
III	2	50	Eq. A	1737.9492	1.0062261	-0.4405978	-	-
III	2	100	Eq. D	-0.001166	0.2427845	-16.949773	924.93652	-
III	4	0	Eq. A	1695.3459	1.0081499	-0.4508975	-	-
III	4	50	Eq. A	1521.9599	1.0041984	-0.272479	-	-
III	4	100	Eq. D	-0.0023663	0.354921	-18.952371	1201.16	-
III	6	0	Eq. E	233.33757	0.1807236	2927.9411	-0.830322	-
III	6	50	Eq. D	-0.0026727	0.3861257	-19.093328	1198.0769	-
III	6	100	Eq. D	-0.0054854	0.604789	-25.007723	1534.0413	-
IV	-6	0	Eq. C	14.286351	-24.322312	-2.8154203	-	-
IV	-6	50	Eq. C	14.848828	-28.388124	-2.9396773	-	-
IV	-6	100	Eq. C	15.215195	-31.557912	-2.9966331	-	-
IV	-4	0	Eq. A	1417.7307	0.9661542	-0.5186673	-	-
IV	-4	50	Eq. A	701.9861	0.9569389	-0.1810194	-	-
IV	-4	100	Eq. D	-0.0014343	0.2738379	-18.471373	464.15915	-
IV	-2	0	Eq. C	9.8096307	-7.3464493	-1.343481	-	-
IV	-2	50	Eq. D	-0.001959	0.3585134	-23.642726	634.5643	-
IV	-2	100	Eq. D	-0.0018715	0.3473962	-24.201914	708.18899	-
IV	0	0	Eq. A	3135.9922	1.0078183	-0.7952219	-	-
IV	0	50	Eq. A	2183.5942	1.0005483	-0.5099369	-	-
IV	0	100	Eq. D	-0.0017824	0.350877	-25.570092	1017.3698	-
IV	2	0	Eq. A	2561.6186	1.009353	-0.6253269	-	-
IV	2	50	Eq. A	2148.8362	1.0047625	-0.3851695	-	-
IV	2	100	Eq. A	2174.1709	1.0016168	-0.264482	-	-
IV	4	0	Eq. A	2178.9225	1.0082996	-0.4715468	-	-
IV	4	50	Eq. C	7.0045674	2.2388545	-0.0537346	-	-
IV	4	100	Eq. D	-0.0067764	0.752455	-32.691171	1870.6569	-
IV	6	0	Eq. E	4097.538	-0.8883607	296.50747	0.1697847	-
IV	6	50	Eq. D	-0.0089576	0.9834534	-37.968038	1805.087	-
IV	6	100	Eq. D	-0.0357516	2.8599895	-81.501354	2682.0619	-

¹ Eq. Type: Eq. A: $FC = a \cdot (b^V) \cdot (V^c)$. Eq. B: $FC = a + (b / (1 + \exp(-1 \cdot c + d \cdot \ln(V) + e \cdot V)))$. Eq. C: $FC = \exp(a + b/V + c \cdot \ln(V))$. Eq. D: $FC = a \cdot V^3 + b \cdot V^2 + c \cdot V + d$. Eq. E: $FC = a \cdot V^b + c \cdot V^d$

C SUPPLEMENTARY MATERIAL: CODE SOURCE OF THE MAIN PROCEDURES OF THE APPLICATION IN C# LANGUAGE

```

//Classes:

class Truck
{
public double EnginePower { get; set;}
public double TransmissionEficiency { get; set; }
public int Type{ get; set; }
public double PercTransmissionAxle { get; set;}
public double AreaCabin { get; set;}
public double TotalWeigth { get; set;}
//Constant equals to 0.047285
public double c1 { get; set;}
//Cd: Truck drag coefficient
public double Cd { get; set;}
//Cr: rolling coefficient
public double Cr { get; set;}
//C1 and C2: rolling resistance coefficient
public double C2 { get; set;}
public double C3 { get; set;}
}

//Procedures:

//Truck Aceleration
public static double AceleratedSpeed(double InitialSpeed , double distance ,
Truck truck , double mu, double slope , double elevation)
{
for (int i = 0; i <= distance*100; i++)
{
double F = 9.8066 * truck.TotalWeigth * truck.PercTransmissionAxle * mu;
double Ft = 3600 * truck.TransmissionEficiency * (truck.EnginePower / InitialSpeed);
double Ch = 1 - 0.000085 * elevation;
double Ra = truck.c1 * truck.Cd * truck.Ch * truck.AreaCabin *
Math.Pow(InitialSpeed , 2);
double Rr = 9.8066 * truck.Cr * (truck.C2 * InitialSpeed + truck.C3) *
truck.TotalWeigth / 1000;
double RG = 9.8066 * truck.TotalWeigth * slope / 100;
double R = Ra + Rr + RG;
double a = (Math.Min(F, Ft) - R) / truck.TotalWeigth;
double t = (distance/1000) / InitialSpeed;
InitialSpeed = InitialSpeed + a * t;
}
return InitialSpeed;
}

// Curvature
//Needed three consecutive points (X1,Y1), (X2, Y2) and (X3,Y3)
public static Double Curvature(double X1, double Y1, double X2, double Y2,
double X3, double Y3)
{
double Ratio;

```



```

double a = Math.Sqrt(Math.Pow(X1 - X2, 2) + Math.Pow(Y1 - Y2, 2)) * 100;
double b = Math.Sqrt(Math.Pow(X2 - X3, 2) + Math.Pow(Y2 - Y3, 2)) * 100;
double c = Math.Sqrt(Math.Pow(X3 - X1, 2) + Math.Pow(Y3 - Y1, 2)) * 100;
double denRatio = (Math.Sin(Math.Acos((Math.Pow(a, 2) - Math.Pow(b, 2) -
Math.Pow(c, 2)) / (-2 * b * c)))) * 2;
if (denRatio < 0.0001 || double.IsNaN(denRatio))
{
Ratio = 0;
}
else
{
Ratio = a / (Math.Sin(Math.Acos((Math.Pow(a, 2) - Math.Pow(b, 2) -
Math.Pow(c, 2)) / (-2 * b * c)))) * 2;
}
return Ratio * 1000;
}

```

```

//Load the elevation using a ASCII DEM
public static double[,] elevationMatrix(double maxX, double minX, d
ouble maxY, double minY, double size, string filepath)
{
int counter = 0;
int counter2 = 0;
string line;
int xid = Convert.ToInt32((maxX - minX) / size);
int yid = Convert.ToInt32((maxY - minY) / size);
double[,] mT = new double[xid, yid];
// Read the file and display it line by line.
System.IO.StreamReader file =
new System.IO.StreamReader(filepath);
while ((line = file.ReadLine()) != null)
{
if (counter > 5)
{
string b = "";
b = line;
for (int i = 0; i < b.Split(new Char[] { ',', ' ' }).Count() - 1; i++)
{
mT[i, counter2] = Convert.ToDouble(b.Split(new Char[]
{ ',', ' ' }).ElementAt(i).ToString());
}
counter2++;
}
counter++;
}
file.Close();
return mT;
}

```

```

//Slope classes
public static int slopeclass(double slope)
{
int slopecase = 0;
slope = slope * 100;

```

```

if (slope < -6) { slopecase = -6; }
else if (slope < -4) { slopecase = -4; }
else if (slope < -2) { slopecase = -2; }
else if (slope < 0) { slopecase = 0; }
else if (slope < 2) { slopecase = 0; }
else if (slope < 4) { slopecase = 2; }
else if (slope < 6) { slopecase = 4; }
else { slopecase = 6; }
return slopecase;
}

```

```

//Establishment of max legal velocity classes
public static Double maxVel(string HighwayType)
{
if (HighwayType == "motorway") { return 100; }
if (HighwayType == "trunk") { return 80; }
if (HighwayType == "primary") { return 80; }
if (HighwayType == "secondary") { return 70; }
if (HighwayType == "tertiary") { return 70; }
if (HighwayType == "unclassified") { return 80; }
if (HighwayType == "residential") { return 40; }
if (HighwayType == "service") { return 30; }
if (HighwayType == "motorway_link") { return 60; }
if (HighwayType == "trunk_link") { return 60; }
if (HighwayType == "primary_link") { return 50; }
if (HighwayType == "secondary_link") { return 50; }
if (HighwayType == "tertiary_link") { return 50; }
if (HighwayType == "living_street") { return 30; }
if (HighwayType == "pedestrian") { return 20; }
if (HighwayType == "track") { return 20; }
}

```

D SUPPLEMENTARY MATERIAL: DISTRIBUTION OF FUEL CONSUMPTION AND CO₂ EMISSIONS FOR TRUCK TYPES II, III AND IV.

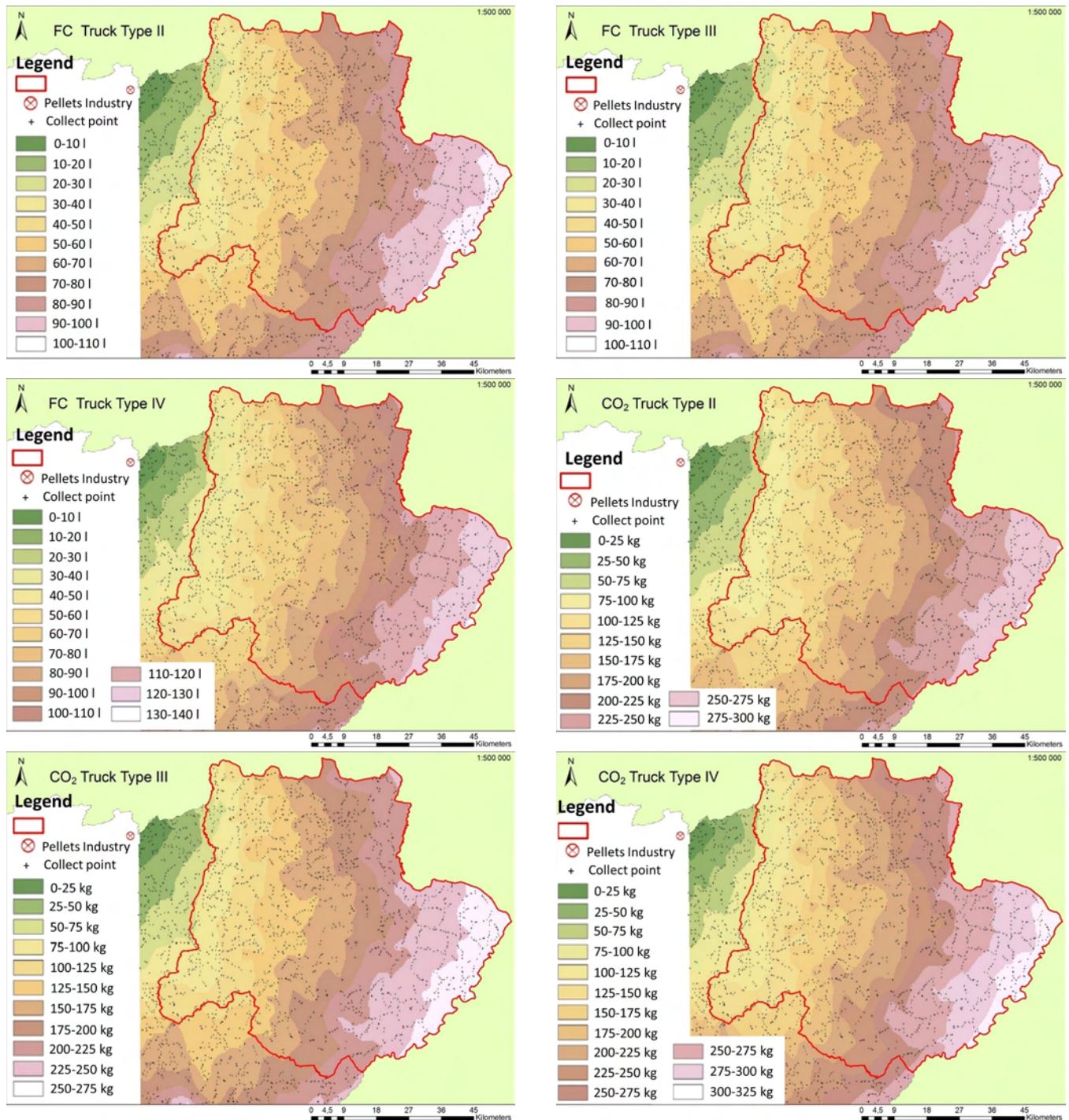


Figure 7: Fuel Consumption for the Nordeste Transmontano region, Portugal, in relation to a starting point corresponding to a wood pellets plant, for (from top left to bottom right): a) for truck type II (Rigid big); b) truck type III (Articulated small); c) truck type IV (Articulated big); d) truck type II (Rigid big); e) truck type III (Articulated small); and f) truck type IV (Articulated big).