Vehicle Movement Environmental Externality Score

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Introduction

Modelling approaches for predicting environmental externalities (e.g. estimate CO2 emissions) from vehicle movement are based on the estimation of fuel consumption. The latter is based on several factors, the most popular being distance, time, type of fuel, type of vehicle (e.g. body style, model year, type of engine etc.), weight load and mode of operation (e.g. different engine management concepts, gear-shift philosophies etc.). The vehicle, as the source of the emissions, is a very important component for the evaluation and estimation of environmental externalities in the transport sector. However, there is another important component that affects the amount of emissions produced by vehicle transportation that has been taken either partially or not at all under consideration. This component is related to the characteristics of the transportation network. The transportation network is the recipient of the emissions, but at the same time its specific characteristics affect the amount of emissions. The transportation network is composed by nodes which correspond to intersections and arcs that connect two nodes. An arc is characterised by a number of factors (henceforth, referred to as Transportation Network (TN) factors) which definitely influence fuel consumption and emission production if this arc is used independently of the vehicle chosen to traverse the arc.

In this research, we develop a function that takes as input static/dynamic and quantitative/ qualitative data and estimates a score for each arc of the TN, referred to as the Environmental Externalities Score (EES) of the arc or EESarc. The EESarc approximates the potential for environmental externalities if the arc is used. The EESarc represents the percentage of increase or decrease of environmental externalities per kilometre, compared to the same arc under nominal conditions for certain parameters, defined by the TN factors. EESarc values dependent solely on the parameters affected by the TN factors and the length of the arc but are independent of other fuel consumption factors.

The EESarc is introduced in the framework of the GreenRoute project (Marie Curie FP7-People, www.GreenYourRoute.com) to define the objective function of a mixed integer linear programming model representing the environmental Traveling Salesman Problem (TSP). The environmental TSP refers to the problem of designing optimal routes start from an initial geographical point, defined by the user of the environmental routing platform (the final outcome of GreenRoute project), traverse a subset of points in an optimal (i.e. minimizing environmental externalities) sequence and return to the initial point. The solution of the environmental TSP defines as optimal route (among all available routes) the one with the minimum percentage of increase of environmental externalities per kilometre. Each feasible route is composed by a number of arcs that may have different EESarc values. The optimal route corresponds to the one with the minimum sum of EESarc multiplied by the arc length, over all the arcs of the route. In the following section, we define the TN factors, the parameters that they affect, and their nominal conditions, followed by a section where EESarc function is presented. In the last section, numerical examples are used to demonstrate the utility of the EESarc function in defining environmentally friendly routes.

Transportation Network (NT) factors

Transportation Network (**TN**) factors are defined as the factors that represent conditions (i.e. traffic, infrastructure, weather) occurring on a transportation network. These factors are not dependent on the vehicle characteristics, but influence the performance and fuel consumption of the vehicle, and therefore its associated emissions. The TN factors taken under consideration are classified into three categories: 1) *Traffic Conditions*, 2) *Infrastructure Profile*, and 3) *Weather Conditions*. Each category includes a number of subcategory factors, referred to as subTN factors, depicted in Figure 1.

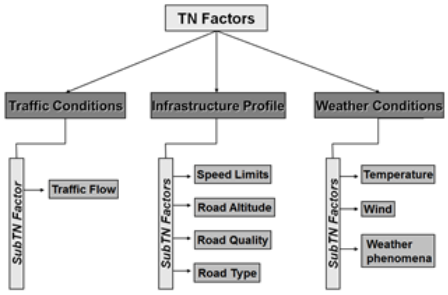

Figure *1*: TN factors and SubTN factors.

TN factors provide the required components for the development of the EES and define the types of data required for the implementation of EES. These data are classified into static/ dynamic and quantitative/qualitative. In general, subTN factors affect parameters responsible for the production of emissions. The parameters taken under consideration are:

a) The *driving speed* of the vehicle defined by the traffic flow, speed limits, road quality and weather phenomena subTN factors. This parameter's nominal value corresponds to the maximum speed limits condition;

b) The *gradient* of the road defined by the road altitude subTN factor. This parameter's nominal value corresponds to a 0% gradient condition;

c) The *rolling resistance* of the road defined by the road quality and road type subTN factors. This parameter's nominal value corresponds to the conditions of a newly constructed pavement of a highway;

d) The *usage of Air Conditioner (AC)* defined by the temperature subTN factor. This parameter's nominal value corresponds to temperatures between 20 to 28^0C;

e) The *air resistance* defined by the wind subTN factor. This parameter's nominal value corresponds to a no-wind condition;

f) The *driving visibility* defined by the weather phenomena subTN factor. This parameter's nominal condition corresponds to the no-rain, no-fog or no-snow conditions.

Traffic Conditions TN factor

The Traffic Conditions TN factor is defined by the type of traffic flow that exists while the vehicle is moving on a specific arc of the road. More precisely, the Traffic Conditions TN factor includes one subTN factor, namely the *traffic flow*. The traffic flow is defined as the total number of vehicles passing a given point in a given time and is measured in vehicles per hour. Traffic flow affects the driving speed parameter, as travel delays lead to a decreased speed as well as increased fuel consumption and hence Greenhouse Gas (**GHG**) emissions.

Pollutant emissions are relatively sensitive to the driving speeds. Thus, a certain level of detail in the speed description is necessary for an accurate evaluation of emissions. Driving speed is the main parameter of the traffic flow subTN factor, which is widely used to describe real traffic situations (Tamsanya, Chungpaibulpattana, & Atthajariyakul, 2006). One practical method to determine driving speeds is calculated from traffic flow simulation models as well as other approximation methods which are based on the traveled time and distance. In the framework of this research, four discrete traffic conditions are defined: a) *free flow speed* conditions (no traffic congestion), b) *low congestion*, c) *moderate congestion* and d) *heavy congestion*. There have been several research studies on the effect of traffic on speed and fuel consumption as well as the influence on the pollutant emissions (André & HammarstrÖm, 2000). Most of emission models estimate emission rates involving traffic flow and speed because they are easily quantifiable (Pandian, Gokhale, & Ghoshall, 2009). In such models, the instantaneous fuel consumption as well as GHG emissions are determined as a function of the actual speed (Treiber, Kesting, & Thiemann, 2007) & (Zhang, Batterman, & Dion, 2011) which is correlated to the traffic flow subTN factor.

Infrastructure Profile TN factor

The Infrastructure Profile TN factor is defined as the physical structural features of a road and consists of four infrastructure profile subTN factors: a) *speed limits*, b) *road altitude*, c) *road quality* and d) *road type* subTN factors.

The speed limit is the limit of speed allowed by law for road vehicles. Speed limits may define maximum (which may be variable), minimum or no speed limit. The speed limit is adjusted according to weather, traffic conditions, and construction on a road. Current speed limits differ across EU Member States, and the competence to define them generally lies with national governments. Some countries with areas of extreme changes in driving conditions also apply variable speed limits, related to traffic and weather conditions. The driving speed parameter is affected not only by the traffic flow subTN factor but also by the speed limits subTN factor. The driving speed influences fuel consumption and emission of air-polluting substances (Den Tonkelaar, 1994) & (Den Tolkelaar, 1999). It is generally admitted that pollutant emissions are dependent on the speed level. Indeed, emissions, currently measured as a function of the average speed of a driving cycle, show a clear speed dependency. In fact, emissions estimation can be affected by as much as 30% of the driving speed data quality (André & HammarstrÖm, 2000).

The road altitude subTN factor is defined as the elevation of the road above sea level. For each point on a route, a specific altitude on the road can be measured. If the altitude's difference between two points of a transportation network is positive, then the produced GHG emissions increase significantly compared to the zero or negative difference (between two points of transportation network). The altitude's difference between two points of a transportation network is strongly related to the gradient of a road parameter. The gradient of a road is defined as a measure of the road's steepness as it rises and falls along its route. In other words, it is the magnitude of its incline or slope. The amount of grade indicates how much the road is inclined from the horizontal. For example, if a section of road is perfectly flat and level, then its grade along that section is zero even if its altitude is above the sea level. Gradients can be expressed either in terms of a percentage compared to the sea level or in terms of an angle, in degrees in relation to the horizontal. The greater a grade, the more power is required by a vehicle at a given speed. Therefore routes with lower or zero grades are preferred, as long as they do not have other disadvantages, such as causing the overall travel distance to increase significantly. Vehicles proceeding up a steep grade demand more fuel consumption with typically increased air pollution generation. The gradient of a road has the effect of increasing or decreasing the fuel consumption and the Hydrocarbons, CO, and NO_x emissions of the vehicles. Increases or decreases in the load on the engine have a corresponding effect on rates of emission and fuel consumption, but even in the case of large-scale applications, it cannot be assumed that the extra emission, when travelling uphill is fully compensated by the reduced emission when travelling downhill (Hickman, 1999). In principle, the emissions and fuel consumption of both light and heavy duty vehicles are affected by road gradient. It must be noticed that in the case of slight gradients, in the range between -2% and 2%, it can be assumed with sufficient accuracy that these do not affect the driving behavior. On the other hand, in the case of steeper gradients above 4% and mean speeds above 50 km/h, this assumption is no longer permissible. Consequently, special driving patterns could be derived for gradients beyond 2% and respectively -2% (Joumard, 1999). (Pierson, et al., 1996) showed that emissions uphill are higher than downhill. More specific, emission rates uphill (grades 0 to 3.76%, average 3.3%) were double the emission rates downhill (0 to -3.76%, average -1.8%). In accordance to (Pierson, et al., 1996) also (Harris, 2005) pointed out that uphill driving generates significant more emissions than downhill driving.

The quality of a road subTN factor corresponds to the pavement quality (defined by its age and use). The pavement quality influences the rolling resistance of the vehicle. The rolling resistance parameter represents the energy dissipated by the tires per unit of distance travelled and describes the vehicle energy loss associated with the pavement-vehicle interaction. The experimental results reported in the literature provide some direction and preliminary numerical ranges of the pavement's effect on fuel consumption. The impact of rolling resistance is highly dependent upon traffic levels and vehicle distribution. High volume roads with heavy truck traffic are affected far more than low volume roads carrying very few trucks. For this reason, the contribution of rolling resistance to the overall environmental impact varies widely from pavement to pavement based on individual traffic conditions (Santero, Masanet, & Horvath, 2011). As a result, the driving speed, which is affected by traffic flow and speed limits subTN

factors, is also influenced by the road quality subTN factor. Referring to (Beuving, De Jonghe, Goos, Lindahl, & Stawiarski, 2004), reducing the rolling resistance loss can contribute significantly to the overall fuel requirements, as the smoother the road is, the lower the fuel consumption. Approximately, 12% of the fuel consumption for heavy trucks is accounted for by the rolling resistance losses in the tires at a constant speed of 80 km/h. This energy loss represents approximately 30% of the available mechanical power from the engine crankshaft. For passenger cars driving at a constant speed of 100 km/h, the rolling resistance accounts for 25% of the available mechanical engine power output, as passenger cars are normally overpowered and therefore have less efficient running engines, in particular gasoline fuelled engines. As a percentage of the fossil fuel input it is estimated that rolling resistance losses account for 15% to 20% for such vehicles.

Different types of roads exist around the world. The road type subTN factor is mainly classified into three categories: i) urban road, i.e. a road within the boundaries of a built-up area, which is an area with entries and exits especially sign-posted as such, ii) rural road, i.e. a road consisting of those facilities that are outside small urban and urbanized areas and iii) highway, i.e. any public road of high speed limits. The road type subTN factor defines the driving speed and traffic flow parameters. Each road, based on its type, has different speed limits. Taking into account two traffic conditions, normal and congested, (De Vlieger, De Keukeleere, & Kretzschmar, 2000) observe that the highest fuel consumption rates and emissions values were produced in urban roads compared to rural and highway roads. According to (Brundell-Freij & Ericsson, 2005), street type with the associated speed limit, as well as traffic conditions has an influence on exhaust emissions and fuel consumption. Street function was coded at three levels: local streets, main streets, and arterial streets corresponding to three speed limit classes, 50 km/h, 70 km/h and 90 km/h. Therefore, the category of street is critical to assess the environmental effects, as emissions are generally calculated based on vehicle kilometers in particular traffic situations, based on the type of road.

Weather Conditions TN factor

The weather conditions TN factor is defined as the set of weather conditions, occurring in an arc of a road, at a certain point in time and influence the vehicular movement. Weather conditions TN factor is divided into three subTN factors: a) *temperature*, b) *wind* and c) *weather phenomena* (i.e. rain, fog, snow).

Ambient temperature is of vital importance as it defines the usage or not of the heating or cooling (air conditioner) system. The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE, 1992) defines an ambient temperature of 23°C as the ideal default temperature that maximizes the thermal comfort of passengers. The climatic conditions and set temperature have certainly a huge influence on Air-Condition (AC) running, and then on pollutants emissions. Fuel consumption due to AC has to take into account climatic conditions, which depend on temperature subTN factor. The excess fuel consumption due to AC is well known in warm conditions, as AC system is running quite close to the full load at the test conditions (outside temperature higher than 28°C) (Roujol & Joumard, Influence of passenger car auxiliaries on pollutant emission factors within the Artemis model, 2009) & (Roujol, 2005). The influence of AC activity on emissions and fuel consumption of passenger cars is of major significance, since it leads to increased fuel consumption and hence emissions. AC causes increased fuel consumption and thus additional CO2 emissions that increase significantly with temperature and lower vehicle speed, whereas AC efficiency decreases significantly with higher vehicle speed, (Weilenmann, Vasic, Stettler, & Novak, 2005). According to (Silva, Farias, Christopher Frey, & Rouphail, 2006), AC use increases power consumption by 2 kW, on average, for light-duty vehicles. More precisely, for cruise speeds of 10 to 120 km/h, and for several stop and go situations, an increase of 6 to 67% in fuel consumption and CO_2 emissions (relatively to the runs without AC), 3 to 8% increase in HC, 6 to 140% increase in CO and 7 to 230% in NO_x emission is pointed out. In accordance to (Cicero-Fernandez & Long, 1995) study, for AC operation, tests were performed on two hills (positive grades: 4.5% and 6.7%) at three speeds. The emission rates of hydrocarbons showed an increase of 57%, when AC at a maximum setting was used. For CO, the increase was 268% for AC operation. The analysis included the positive grade fraction of the runs. The distance based emission rates of hydrocarbons showed an increase of 57%, when AC at a maximum setting was used.

Wind subTN factor affects fuel consumption through added resistance on the vehicles' motion, called air resistance or drag force. There is a strong relationship between speed and air

resistance force, as certainly more speed means more force. Wind force and direction also affects heavily the GHG emissions. Wind resistance plays a very important role in determining fuel consumption and emissions. The air resistance coefficient may vary widely from one vehicle type to another, especially for heavy-duty vehicles (Joumard, 1999). Fuel consumption increases with the tractive energy required by the vehicles to overcome air resistance or drag force (Sovran, 1983). The effect of wind is a factor, which can be quantitatively estimated for fuel consumption and hence GHG emission generation. Wind subTN factor can affect both a rolling resistance parameter (affected also by road quality and type) and aerodynamic drag. Rolling resistance is primarily affected by a side wind, which pushes the vehicle sideways. This increases the drag caused by the tires on the road way surface. However, the effect of wind on aerodynamic drag is far the larger of the two effects (EPA, 2006). While aerodynamic drag is much lower at city driving speeds than highway speeds, wind speed is a higher fraction of vehicle speed at low vehicle speeds. The effect of wind on a vehicle's effective drag coefficient increases as the effective angle of the air speed increases. Thus, the effect of a side wind can be significant, even at low vehicle speeds. At low vehicle speeds, the tractive force is dominated by rolling resistance, whereas at high vehicle speeds aerodynamic resistance dominates. Hence, it is more important to accurately model aerodynamic resistance at higher vehicle speeds, (N.D. Lea International Ltd;, 1995).

Weather phenomena are regarded as the temporary weather conditions occurring at a specific point in time on an arc of a road. Weather phenomena subTN factor includes rain, fog and snow. They comprise the factors that cause the reduced visibility on a road, which has as a consequence the speed decrease. As a result, weather phenomena subTN factor has an influence on a vehicles' speed. Consideration has been given to the effect of weather conditions on free-flow speed. According to several studies, the effects of a variety of weather-related environmental factors on driver speeds has generated substantial data on traffic flow rates and driver speeds during periods of reduced visibility and other hazardous driving conditions. Moreover, weather conditions do play a factor of increasing or reducing fuel consumption and the associated emissions. (Ibrahim & Hall, 1994) studied the effects of rain and snow on speed flow occupancy relationships, summarizing their findings into three categories: clear and rainy weather, clear and snowy weather, and rainy and snowy weather. Under the condition of free-flow speed, the authors pointed out reduction on vehicle speed. In particular, light rain caused a 2 km/h drop, light snow a 3 km/h drop, heavy rain a 5 to 10 km/h drop and eventually heavy snow caused a 38 to 50 km/h drop. Furthermore, (Kyte, Khatib, Shannon, & Kitchener, 2000) indicated that snow or ice on the roadway reduces vehicle speeds by nearly 10 km/h below dry pavement conditions. (Liang, Kyte, Kitchener, & Shannon, 1998) reported on the effects of snow and fog on driver speed. They found 8 km/h reduction of driver speed during fog events and a 19.2 km/h reduction during snow events.

Environmental Externality Score

An arc of a transportation network has certain characteristics some of which stay constant (e.g. infrastructure profile and length of an arc) and some of which change dynamically over time (e.g. traffic and weather conditions). The Environmental Externalities Score of an arc (EES_{arc}) approximates the potential for environmental externalities if this arc is used and it could be expressed as fuel consumption (FC) or any other emissions factor (CO, NOx, PM etc.). EES_{arc} is estimated based on the traffic conditions TN factor, the infrastructure profile TN factor, the weather conditions TN factor and the length of the arc under consideration and in the framework of this paper is expressed in terms of FC. The following A-B arc of a transportation network (see Figure 2) corresponds to a highway with speed limit 80 Km/h. In A-B arc no weather phenomena, wind and traffic are observed. Under these conditions the parameters of driving speed, air resistance and driving visibility are in nominal conditions contributing 0% to the EES of the arc.

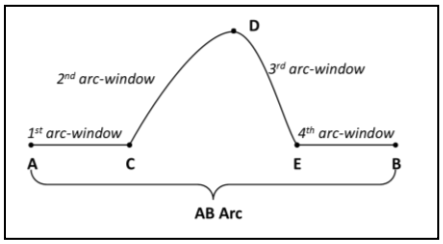

Figure *2*: TN factors and SubTN factors.

Each arc is composed of certain number of arc windows. An arc-window is defined, as the part of the arc over which the parameters defined by of TN factors have a common state, i.e. no change in the states (e.g. value) of the parameters affected by the subTN factors is observed. The A-B arc is composed of 4 arc-windows where the parameters are observed to be in the same state. For example the 2nd arc-window C-D is defined due to the temperature change compared to A-C arc-window, resulting in the use of the AC, and the altitude change between point C and D, resulting in a gradient of 6%. Table 1 presents the conditions for each parameter affected by the subTN factors, for each arc-window.

Table 1: The Parameters' condition

Parameter	Arc-window 1 A-C	Arc-window 2 C-D	Arc-window 3 D-E	Arc-window 4 E-B
Driving speed	Speed limit (80 Km/h)	Speed limit (80 Km/h)	Speed limit (80 Km/h)	Speed limit (80 Km/h)
Gradient	0%	+6%	-6%	0%
Rolling resistance	5 years old Pavement	5 years old Pavement	5 years old Pavement	5 years old Pavement
Using or not of AC	No 23°C	Yes (17°C)	Yes (17°C)	No 23°C
Air resistance	No wind	No wind	No wind	No wind
Driving visibility	Clear	Clear	Clear	Clear
Length (Km)	100	120	120	140

Table 1 shows that for some arc-windows three parameters (i.e. gradient, rolling resistance and use of AC) are not in nominal condition contributing to the increase (e.g. use of AC) and/or decrease (e.g. downhill) of the EESarc. In order to approximate the percentage of increase or reduction of environmental externalities compared to the nominal conditions of the parameters affected by TN factors, we have conducted a detailed bibliography search. Our objective was to find theoretical and experimental research results, showing the correlation between fuel consumption (and thus emissions production) and one or more of the under examination parameters affected by the subTN factors. The experimental results presented in (Hasse & Weber, 1997), (Zhang & Frey, 2005), (Helms & Lambrecht, 2006), (Boriboonsomsin & Barth, 2009) show that with a driving speed of 80 Km/h an average FC increase of 157% per kilometer traveled on a road with a gradient of +6% and an average decrease of 90% per kilometer traveled on a road with a gradient of -6% should be expected when compared to a zero gradient road. Based on these data the total contribution of the gradient to the total EESarc in the example in figure 2 is equal to 16.75% per kilometer (see Table 2).

Table 2: Gradient contribution

	Arc-window A-C	Arc-window C-D	Arc-window D-E	Arc-window E-B
Gradient	0%	+6%	-6%	0%
Contribution per kilometer	0%	157%	-90%	0%
Length (KM)	100	120	120	140
Contribution to A-B arc	0%	157%*(120/480)	-90%*(120/480)	0%
Total contribution of gradient to A-B arc of 480 Km length = 16.75% per kilometer				

The experimental results presented in (Gillespie & McGhee, 2007) with a driving speed of 80 Km/h show that the average increase of FC on a highway with a pavement of five years old compared to a new pavement is equal to 2.15% per kilometer traveled. Based on this data the contribution of rolling resistance to the total EESarc is equal to 2.15% per kilometer since the arc A-B has the same pavement along the 4 arc-windows. The experimental results presented in (Roujol & Joumard, 2009), (Koupal, 2001) with a driving speed of 80 Km/h show that the average increase of FC on a highway when the AC used by a vehicle (due to the low

temperature, 17°C) compared to case where AC is off is equal to 11.33% per kilometer traveled. Based on these data the contribution of the AC to the total EESarc in the example presented in Figure 2 is equal to 5.665% per kilometer (see Table 3).

Table 3: AC contribution

	Arc-window A-C	Arc-window C-D	Arc-window D-E	Arc-window E-B
Air Condition	No use	Use	Use	No use
Contribution per kilometer	0%	11.33%	11.33%	0%
Length (KM)	100	120	120	140
Contribution to A-B arc	0%	11.33%*(120/480)	11.33%*(120/480)	0%
Total contribution of AC to A-B arc of 480 Km length = 5.665% per kilometer				

Summarizing the above contributions, the total EESarc is equal to 24.565% per kilometer (16.75% related to gradient, 2.15% related to the age of pavement and 5.665% related to AC) for the first alternative road presented in Figure 2. Consider now a second alternative road which connects point A and B (length of 750Km, 56% longer than the first alternative road) where all parameters are in nominal conditions. In that case the EESarc will be equal to 0% per kilometer. Additionally, consider a third alternative road connecting A and B where the road gradient is 4% (uphill of 160 Km length) and 4% (downhill of 160 Km length), the AC is on for the entire traveled distance (540 Km) and all other parameters are in nominal condition. Based on the above methodology the total EESarc will be equal to 24.07% per kilometer. Table 4 summarizes the EESarc and FC for each alternative road.

Table 4: EESarc for the three alternative roads connecting A and B

	EESarc	Length	FC/KM	FC = (1+EES)*Length*FC/km
First alternative	24.565%	480		36 l
Second alternative	0%	750	0.06 l/Km	45 l
Third alternative	24.07%	540		40 l

Based on EESarc function the route with the minimum environmental externalities, between the three alternatives, is the first. The first alternative will always be better than the second alternative if the length of the second alternative is always larger than 24.565% (a value which corresponds to the contribution of parameters which are not in nominal condition in the first alternative). Another interesting result is that even if the third alternative has a smoother slop (4% as compared to 6% of the first alternative) it will still have higher environmental externalities as the total length of uphill and downhill part is much longer than in the first alternative.

Conclusions

In this paper we have presented a methodology to calculate a score for the potential environmental externalities when the same driver using the same vehicle could traverse a number of alternative routes which connects the same start and end point. An arc of a transportation network has certain characteristics some of which stay constant (e.g. infrastructure profile and length of an arc) and some of which change dynamically over time (e.g. traffic and weather conditions). The Environmental Externalities Score of this arc (EES_{arc}) approximates the potential for environmental externalities if this arc is used and it could be expressed as fuel consumption (FC) or any other emissions factor (CO, NOx, PM etc.). EES_{arc} is estimated based on the traffic conditions TN factor, the infrastructure profile TN factor, the weather conditions TN factor and the length of the arc under consideration and in the framework of this paper is expressed in terms of FC. The calculation of EESarc has been conducted based on average values from experimental results found by our bibliographic review. In reality the alternative routes connecting two places have in general significant different conditions for each

one of the parameters affected by subTN factors and important difference in their length. The average values give an indication about the environmental externalities which even if they are not sufficient for the emission and fuel consumption calculation they can be sufficient for the selection of the optimal route as it was shown through the presented numerical examples. Finally, a beta version of the platform is available at http://194.177.201.88/greenroute where only the gradient parameter is taken under consideration for the calculation of the optimal route. The full version of the platform will be available in 2014.

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