A METHODOLOGY FOR ESTIMATING TRAFFIC FUEL CONSUMPTION AND VEHICLE EMISSIONS FOR URBAN PLANNING

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1. Introduction

One of the main issues within urban planning concerns the reduction of energy consumption and emissions produced by industry, public services, transport system, and the like. Today, transport energy consumption and emissions account for about 20%-40% of the total. In such a context, effective estimation of transport impacts should be envisaged and strategies/policies for their mitigation proposed.

Recently the Urban Energy Plan (UEP) was introduced as a fundamental step of urban planning activities. The UEP is a strategic plan which aims to reduce energy consumption and pollutant emissions produced by several sectors. Adoption and implementation of UEPs is obligatory in certain EU Member States. Some cities adopt plans on a voluntary basis to improve quality of life or in order to comply with EU standards to protect human health (e.g. air quality).

In the literature, estimation of energy consumption and vehicle emissions is usually carried out by the application of mathematical models that allow estimation of average concentrations by means of variables representing the characteristics of the travel demand (e.g. origin-destination matrix, the composition of the vehicle fleet, the average length of trips) as well as variables representing the traffic flow conditions (e.g. average speed, vehicle density). These input variables can be estimated through surveys or through simulation models. In the former case, we can only estimate the impacts compared to a base scenario (current); in the latter case, it is possible to estimate impacts with regard to design scenarios (e.g. changes in the socio-economic system, modal split variation, traffic congestion reduction).

The most pursued approaches are often aggregated and use input variables estimated through surveys. Those approaches that implement disaggregated models are based on simulation models, but refer only to small portions of the transport system (e.g. single individual intersections or roads) and do not allow evaluation of the impacts on the entire system.

This paper proposes a method to estimate traffic fuel consumption and emissions at urban scale. The aim is threefold: (i) to propose a methodology which, pursuing a disaggregate approach, integrate transportation models with fuel consumption and emission models; (ii) to estimate global performance indicators; (iii) to carry out a sensitivity analysis with respect to the input variables such as: vehicle types, modal split, vehicle flow density. The proposed methodology also allows us to evaluate the effects of travel demand management strategies.

The innovative elements of the proposed methodology are:

- disaggregated estimation of the input variables; for each vehicle type it is possible to estimate average vehicle speeds and average trip lengths (generally estimated in an aggregate way through surveys and not as output of a transportation model);
- disaggregated estimation of travel demand by vehicle type;
    - internal-internal demand estimation; this travel demand concerns trips with both origin and destination within the study area (such vehicle flows are generally estimated coincident with the number of vehicles registered in the study area);
    - internal-external demand estimation; this travel demand is related to trips with origin within the study area and destination external (such vehicle flows are generally estimated approximately);
    - external-internal demand estimation; this travel demand is related to trips with origin outside the study area and destination inside (such vehicle flows are generally ignored);
- estimation of a model able to quantify the effect of some transport system modification in terms of vehicle consumption and emission variations; this allows impacts to be estimated with respect to design scenarios (generally models proposed in the literature are only able to estimate impacts compared to a base scenario).

The methodology was applied to the city of Salerno (Italy) and is part of the actual UEP. It is based on consolidated methods/models of transportation system analysis. As regards the estimation of fuel consumption and emissions, the European approach based on COPERT method was pursued.

The paper is divided into four sections; in the first a brief state of art is proposed, in the second the estimation methodology is presented; in the third application to a real case is described, while the fourth reports the conclusions.

2. State of art

Traffic fuel consumptions and vehicle emissions estimation models proposed in the literature should be classified according to the geographical area where they were calibrated (estimation of model parameters). This is because some conditions such as the traffic flow (average speed, accelerations and all mobility behaviors in general), geometric infrastructure (width, radii of curvature, slopes, lateral disturbance index) and environment (average temperature, altitude, rainfall index, characteristics of the wind etc..) influence, in a non-negligible way, traffic-derived emission and consumption factors. According to such a classification, most of the models developed in the literature were estimated in the USA and Europe, amongst which the most widely used are (for a state of the art see for example Ardekan et al, 2002):

USA models

- MICRO2 Model (Richards, 1983);
- California Line (CALINE) Model (Federal Highway Administration (1984);
- Urban Mass Transportation Administration (UMTA) Model (1985);
- Mobile Source Emission Factor Model – MOBILE 6 (U. S. Environmental Protection Agency, 1991);
- Motor Vehicle Emission Factor (EMFAC) Model (Environmental Protection Agency, 2003).

European models

- TRLL Model (Hickman and Waterfield, 1984);
- COmputer Programme to calculate Emissions from Road Transport – COPERT 4 (European Environment Agency, 1997 and 2000);

MICRO2 is a model which gives an estimation of the traffic pollutant emission near single individual intersections; this model allows estimation of the concentrations emitted from vehicles as a function of acceleration, speed and environmental variables such as speed and wind direction.

CALINE is a model developed by the California Department of Transportation to assess the impact of the air quality close to a transportation infrastructure according to the geometry of the infrastructure, the surrounding landscape and weather conditions. Using this model it is possible to estimate the concentrations of pollutants close to receptors placed up to 500 meters from the infrastructure; the input variables of the model are: wind direction and speed, atmospheric stability, average ambient temperature, traffic flows, the unit emission factors for each vehicle category and location of the receptor.

UMTA is, perhaps, the simplest model among those developed in the USA, and it correlates the average vehicle speed with the average emission levels for highways and urban roads. For the estimation it uses a combination of free flow speed (weighing two-thirds of the trips) and congested flow speed (weighing a third of the trips).

MOBILE is perhaps the most widely used model for estimating the emissions of mobile sources in the USA. This model can estimate the concentration of hydroxyl carbon (HC), carbon monoxide (CO) and nitrogen oxides (NOx) emitted by both diesel and gasoline powered vehicles. This model allows explicit consideration of eight distinct types of vehicles in two different spatial contexts: low and high latitudes. The estimates depend on factors such as temperature, average vehicle speed and average trip distance.

EMFAC is a model developed by the California Environmental Protection Agency to estimate average vehicle emissions of hydrocarbons, carbon monoxide, particulate matter, sulphur and carbon dioxide; based on historical series, the model provides an estimation with reference to a timeframe ranging from 1970 to 2040. The vehicle categories considered are passenger cars, light and heavy goods vehicles, motorcycles, school buses etc. Also for this model the input variables, besides of the composition of the vehicle fleet, are average travel speeds, the average trip distance and environmental conditions such as the average air temperature.

With regard to the estimated relations in Europe, one of the first models, developed in UK, is TRLL, which allows the estimation of hourly average concentrations of carbon monoxide at specific points of the road network. The input data are: the configuration of the road network, the location of the receptors, the average speed and vehicle traffic flows, the direction and wind speed. Hickman and Waterfield (1984) also provide experimental approximated relations to estimate, given the concentration of carbon monoxide, the levels of other greenhouse gases.

Although in Europe several experiments have been carried out to estimate the fuel consumption and emissions from road traffic, the European Community long ago decided to standardize the unit value of the concentration emitted by vehicles by developing an estimation model, COPERT, which has now been taken as reference by all Member States.

This method, financed by the European Environment Agency (EEA) and developed by CORINAIR (COoRdination INformation AIR) team, allows three different emission types to be estimated: hot emissions, cold emissions and evaporative emissions. The sum of these emission types gives the total emissions due to road traffic. Hot emissions are those emissions that occur when the engine and the emission abatement systems (catalysts) reach temperatures of full capacity; they depend on the average trip distance, the average vehicle speed and the vehicle type, as well as the age, weight and cubic volume of the engine. Cold emissions are emitted during start-up of the engine and emission abatement systems; estimation of these emissions depends on the quantity of kms that the vehicle does at “cold”, which in turn depends on the type of vehicle, environmental conditions, the type of route and guidance. Evaporative emissions, instead, are those resulting from the evaporation of the fuel from the tank which occurs both while the vehicle is moving and when it is stationary.

3. Estimation methodology

As stated above, this paper proposes a methodology to estimate traffic fuel consumption and emissions, seeking to overcome some of the limits of the models proposed in the literature. The model system is divided into two sub-models: a transportation system model and traffic fuel consumption and emission model (see figure 1).

Transportation model simulates the relevant interactions among the various elements of a transportation system, supply and demand sub-systems, and allows to estimate the performance of the system by estimating some indicators (average speed and km/year travelled by vehicle category) both related to the base scenario and referring to design scenarios. Traffic fuel consumption and emission model allows us to estimate the impacts of all the simulated scenarios.

In the following sections the models' details are reported.

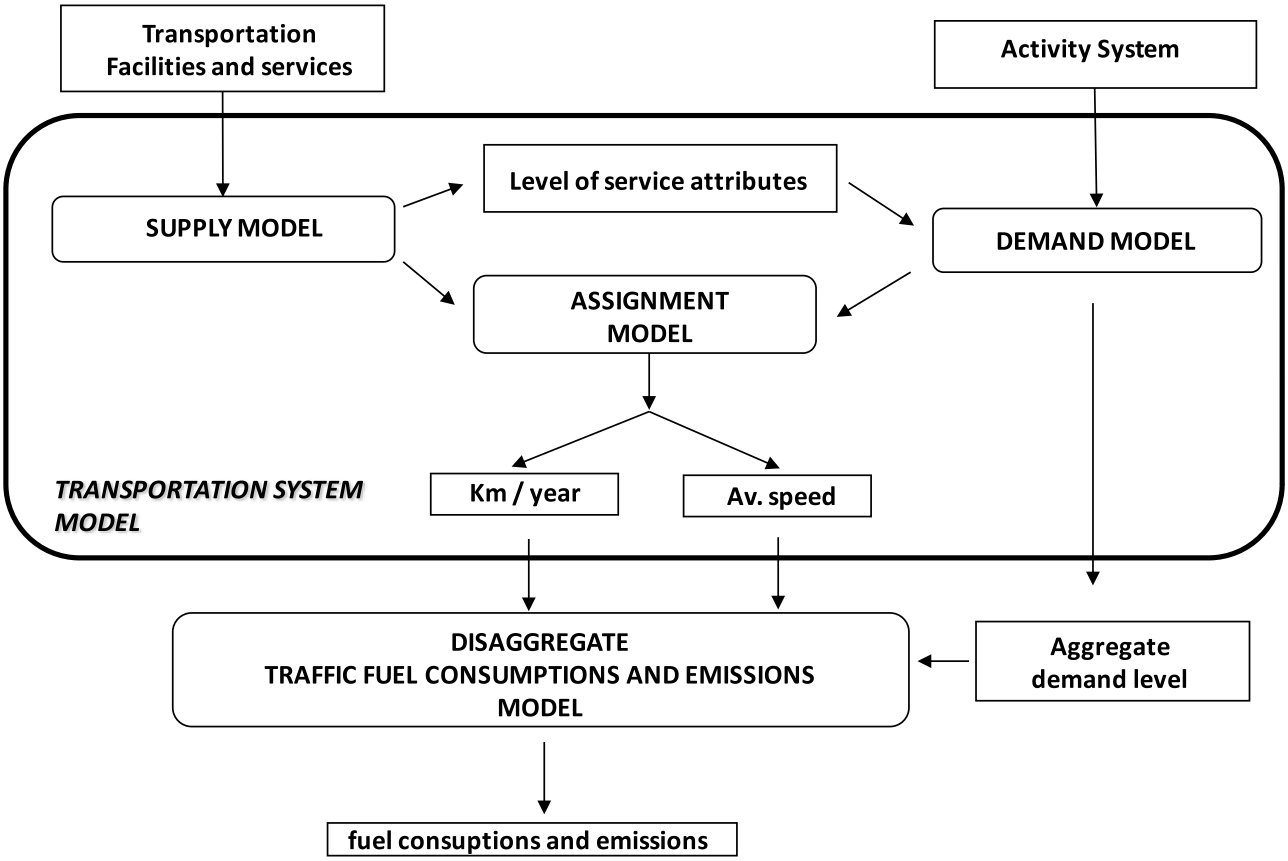

Figure 1: Methodology for estimating traffic fuel consumption and vehicle emissions for urban planning

3.1. Transportation model

The transportation model is constituted of three sub-models: supply model, demand model and supply-demand interaction model. All the three sub-models are based on consolidated approaches of transportation system analysis and are briefly described in the following.

Supply models simulate the performances of the transportation services available in the different zones with flow network models. In particular a synchronic network model was implemented in order to estimate the level of service supplied.

Demand models simulate the aspects of travel demand as a function of the activity system and of the supply performances. Normally, travel demand is considered the most crucial and problematic element to be simulated of a transportation system. Different approaches may be pursued: explicit simulation of travel demand characteristics through transportation demand models (e.g. four-stage model), direct estimation of origin-destination flows estimated through sampling estimators or estimation of origin-destination demand flows using traffic counts. In our case study, the latter approach was developed (the other approaches will be tested in future papers).

Starting from a preexisting origin-destination flows vector, aggregate data (traffic counts and more recent aggregate origin-destination flows) were used in order to correct (update) it so that the whole model system is able to reproduce the observed aggregate data. For each vehicle category *cat* considered (type of vehicle, power, fuel type, ECE regulation reference) origin-destination (OD) demand updating through aggregate data is the methodology used for travel demand estimation:

$$\boldsymbol{d}^{*}_{cat} = \underset{x \geq 0}{argmin}\left[z_1\left(\boldsymbol{x}_{cat}, \hat{\boldsymbol{d}}_{cat}\right) + z_2\left(\boldsymbol{v}\left(\boldsymbol{x}_{cat}\right), \hat{\boldsymbol{f}}_{cat}\right)\right]$$

where, $\boldsymbol{d}^{*}_{cat}$ is the estimation result related to the vehicle category *cat*; $\hat{\boldsymbol{d}}_{cat}$ is the vector representing the initial information related to the vehicle OD flows of the category *cat*; $\boldsymbol{x}_{cat}$ is the unknown demand vector; the two functions $z_1(\cdot)$ and $z_2(\cdot)$ can be considered as different “distance” measures: the first measures the “distance” of the unknown demand $\boldsymbol{x}$ from the *a priori* estimate $\hat{\boldsymbol{d}}_{cat}$ while $z_2(\cdot)$ measures the distance of the flows $\boldsymbol{v}(\boldsymbol{x}_{cat})$ obtained by assigning $\boldsymbol{x}_{cat}$ to the network from the traffic counts $\hat{\boldsymbol{f}}_{cat}$ available for the category *cat*. In general, the functional form of the two terms $z_1(\cdot)$ and $z_2(\cdot)$, depends on the type of information available (experimental or non-experimental) and on the probability laws associated with such information (for more details see for example Cascetta, 2009).

The interaction between demand and supply was simulated through a stochastic user equilibrium assignment model which allowed estimation of link flows and performance indicators such as average speed and km/year travelled for each category of vehicle *cat*.

3.2. Fuel consumption and emission model

The methodology for estimating traffic fuel consumption and vehicle emissions proposed in this paper is known in the literature under the name of a bottom-up model. From a series of more or less disaggregated input data (the number of trips, average distance and average speed per vehicle type) the bottom-up method allows estimation of fuel consumption and emissions. As stated above, the European approach based on the COPERT model was pursued.

3.2.1. Traffic fuel consumption model

The methodology used to estimate traffic fuel consumption is based on unit factors (*fc*) dependent on the vehicle category, *cat* (type of vehicle, power, fuel type, ECE regulation reference), and the average vehicle speed (V_m). The average annual consumption (C_{cat}) for each category *cat,* therefore amounts to:

$$C_{cat} = fc(cat, V_m(cat)) \cdot d(cat) \cdot km_{peryear}(cat)$$

where $d(cat)$ is the annual demand for vehicles related to category cat; $km_{peryear}(cat)$ are the average km covered per year by the same vehicle category cat.
In general, $d(cat)$ is the result of mobility demand estimation, while $km_{peryea}(cat)$ and $V_m(cat)$ are two of the possible performance indicators from the transportation model:

$$km_{peryear}(cat) = \frac{\sum_a f(cat)_a \cdot L_a}{d(cat)} \cdot N_{peryear}(cat)$$

$$V_m(cat) = \frac{\sum_a f(cat)_a \cdot L_a}{d(cat)} \Big/ \frac{\sum_a f(cat)_a \cdot t(cat)_a^{cong}}{d(cat)}$$

where:
$f(cat)_a$ is the vehicle flow of category cat related to the road infrastructure a;
L_a is the road infrastructure length a;
$t(cat)_a^{cong}$ is the vehicle travel time of category cat related to the road infrastructure a, under the hypothesis of congested network (times function of flows);
$\frac{\sum_a f(cat)_a \cdot L_a}{d(cat)}$ represents the average length of a path made by a vehicle of category cat;
$N_{peryear}(cat)$ is the average number of trips made each year by a vehicle of category cat;
$\frac{\sum_a f(cat)_a \cdot t(cat)_a^{carico}}{d(cat)}$ is the average travel time by a vehicle of category cat;

Having estimated fuel consumption for each category cat it is possible to estimate the total consumption as the sum of all categories:

$$C_{tot} = \Sigma_{cat} C_{cat}$$

3.2.2. Vehicle emissions model

The adopted methodology calculates three different types of emissions:

- hot emissions (E_{hot});
- cold emissions (E_{cold});
- evaporative emissions (E_{evap});

the sum gives the total emissions from road traffic E_{tot}:

$$E_{tot} = E_{hot} + E_{cold} + E_{evap}$$

The hot emissions (E_{hot}) are those emissions that occur when the engine and the emission abatement systems (catalysts) reach temperatures of full capacity. They depend on the distance covered ($km_{peryear}(cat)$), the vehicle speed ($V_m(cat)$) and the vehicle type, as well as the age, weight and cubic volume of the engine (cat). These emissions are determined by multiplying specific hot emission factors (fe) by the annual demand of vehicles of category cat and by the $km_{peryear}$ done. The specific hot emission factors depend mainly on the car category and on the running speed and, in the absence of experimental data on the local fleet, typical curves are available in the literature, which allow these emission factors to be estimated depending on the running speed assigned and referring to any type of pollutant. Overall it results that:

$$E_{hot}(cat) = fe(cat, V_m(cat)) \cdot d(cat) \cdot km_{peryear}(cat)$$

Regarding cold emissions (E_{cold}), they develop in the initial stage of engine start-up and equipment to reduce emissions. They are calculated as surplus to the emissions that would be generated by all vehicles always working at full capacity temperature. Computation of such emissions depends on the number of kms that the vehicle performs at cold, which in turn depends on the type of vehicle, environmental conditions, the type of route and driving behaviour. For the sake of simplicity, this computation may be made to depend on:

- average trip length of a vehicle in the category *cat*;
- average ambient temperature, preferably in a monthly scale.

The evaporative emissions (E_{evap}), instead, are those resulting from the evaporation of the fuel from the tank which occurs both when the vehicle is moving and when it is stationary.

This emissions type refers only to Volatile Organic Compounds (VOCs) and to gasoline-powered vehicles because diesel fuel, which is only slightly volatile, makes a negligible contribution. In particular, there are three different types of evaporative emissions:

- daily emissions (diurnal) which are caused by the evaporation of fuel as a result of temperature variations;
- shutdown emissions which are caused by latent heat of the engine (when it is shut down) which in turn causes the evaporation of the remaining fuel in the system. They are divided into two classes depending on whether the car has a carburettor or injection. In the first case there are two other types, defined according to the engine temperature (warm or hot);
- running losses which are the normal evaporative losses that occur while driving the vehicle.

In order to estimate both energy consumption and emissions due to road traffic, we used the unit factors proposed by the European Commission, which has long standardized this procedure.

The CORINAIR develops and regularly updates the unit factors for fuel consumption and emissions (CO, NOx, VOC, SO2, CO2), covering different categories and subcategories of vehicles. In particular, unit factors are currently available relating to gasoline cars (divided into three classes of engine power and current year of ECE regulation); diesel cars (divided into two classes of engine power) and Liquefied Petroleum Gas (LPG) cars (other categories such as natural gas-powered can also be customized); light goods vehicles (gasoline and diesel), diesel heavy goods vehicles (three weight classes); buses and motorcycles (three engine power classes).

With regard to gasoline and diesel cars, the relations are expressed by continuous functions according to the average speed (between 10 and 130 km/h), while relations related to other vehicle categories are expressed with reference to three driving conditions (urban, suburban, highway). Coefficients are reported by the Commission of the European Communities (1990) and European Environment Agency (1997 and 2000).

This methodology can be used with different levels of spatial and temporal aggregation. For example, it can be used to estimate the annual national emissions level or for urban estimations.

The model output allows us to estimate concentrations of a wide range of pollutants resulting from combustion and evaporation of the fuel used by vehicles and the corresponding total vehicle energy consumption. Obviously, the more accurate the input data, the more reliable are the estimations.

4. Application

In this section results from the application of the methodology is proposed. First, results on fuel consumptions and vehicle emissions are reported, then a sensitivity analysis is carried out with respect to different intervention strategies on the transportation system.

The methodology was applied to the city of Salerno (Italy) and is part of the UEP. Salerno is a city in the south of Italy, occupying about 60 km^2 with a population of more than 138,000 and a Gross Domestic Product (GDP) of 3.4 million of euro.

The study area was divided into 82 zones. The topological supply model consists of a graph with 538 nodes and 1,172 links; the generalized transport cost associated to each link was estimated as the result of a sum of two terms: the running time (estimated using the function proposed by Cartenì and Punzo, 2007), considering different free flow speeds for the various categories of vehicles considered, and waiting times at intersections (estimated using the function proposed by Doherty, 1977).

For the travel demand updating methodology, different initial OD vectors were considered with respect to the category of vehicle concerned. The aggregate data used are:

- 50 traffic count sections monitored during two different surveys made in 2003 and 2007;
- the ACI database (italian vehicle owner association) related to vehicle share;
- the census of the systematic travel demand made by ISTAT (the Italian national statistic institute);
- the annual bus statistics of the CSTP (the Salerno bus company);
- some available OD estimation for all the categories of vehicle considered.

The travel demand estimation results show that (see Table 1) about 73% of the trips are made by cars, more than 17% are motorcycle trips, about 1% are trips made by bus vehicles, about 2% are heavy goods vehicle trips while about 8% are trips made by light goods vehicles.

Table 1: Salerno vehicle share

vehicle category	**%**
car	72.9
motorcycle	17.3
bus	0.5
heavy goods vehicles	1.5
light goods vehicles	7.8
total	**100.0**

With respect to the systematic travel demand (purpose of trip: work and study), in the average business day, in Salerno, there are more than 91,000 systematic trips (see Table 2); 51% of these are intra-municipality (more than 46,000 trips), while there are about 45,000 trips related to trips with origin or destination outside the municipal area. The Salerno modal share shows that about 55% of daily trips are made by car and motorcycle, 21% are bus trips, 20% are pedestrians while only 4% of trips are made by rail.

Table 2: Salerno systematic travel demand

purpose	intra-municipality	extra-municipality	total
study	21,665	16,592	**38,257**
work	24,860	28,196	**53,056**
total	**46,525**	**44,788**	**91,313**

purpose	intra-municipality	extra-municipality	total
study	57%	43%	**100%**
work	47%	53%	**100%**
total	**51%**	**49%**	**100%**

purpose	intra-municipality	extra-municipality	total
study	47%	37%	**40%**
work	53%	63%	**60%**
total	**100%**	**100%**	**100%**

4.1. Traffic fuel consumption estimation

Using the implemented model system the traffic fuel consumption was estimated (see Table 3). In all, every year in Salerno gasoline consumption is about 12,000 tons while diesel consumption amounts to about 27,000 tons. These values were converted into petrol equivalent tons (pet) through the Global Warming Potential (GWP) coefficients. The GWP is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is a relative scale which compares the gas in question to that of the same mass of carbon dioxide, CO2, (whose GWP is by convention equal to 1). A GWP is calculated over a specific time interval (100 years for this application) and its value must be stated whenever a GWP is quoted or else the value is meaningless.

With respect to these coefficients, in Salerno every year about 43,000 pet are consumed, amounting to about 0.3 per inhabitant and over 14 pet per million of euro GDP. Results related to the different vehicle categories show that, though comprising about 73% of vehicles, cars consume 46% of the pet per year; goods vehicles, about 9% of vehicles, consume about 30% of the pet; buses that make up about 1% of the total consume more than 20% of the pet; while motorcycles, accounting for over 17% of vehicles, consume about 3% of the pet per year.

Table 3: Salerno traffic fuel consumptions

vehicle category	diesel consumption (tons)	gasoline consumption (tons)	total consumption (*pet*)
Car	6,759	10,239	19,587
motorcycle	0	1,034	1,241
bus	9,511	0	10,272
heavy goods vehicles	7,751	34	8,411
light goods vehicles	2,663	336	3,279
total	**26,684**	**11,643**	**42,790**

vehicle category	diesel consumption (tons)	gasoline consumption (tons)	total consumption (*pet*)
Car	25%	88%	46%
motorcycle	0%	9%	3%
Bus	36%	0%	24%
heavy goods vehicles	29%	0%	20%
light goods vehicles	10%	3%	8%
total	**100%**	**100 %**	**100%**

4.2. Vehicle emissions estimation

Through the model system implemented the vehicle emissions has been estimated. The emissions has been divided into greenhouse gases and fine particles:

- *greenhouse gases* are gases in an atmosphere that participate to the greenhouse effect. The main greenhouse gases considered are:
  - carbon dioxide (CO2);
  - carbon monoxide (CO);
  - nitrogen dioxide (NO2);
  - methane volatile organic compounds (CH4);
  - other volatile organic compounds (VOC);
  - equivalent carbon dioxide (*eq.CO2*).
- *fine particles* are tiny subdivisions of solid or liquid matter suspended in a gas or liquid; it is possible to classify:
  - PM10 are the particles of 10 micrometers or less;
  - PM2.5 represents particles less than 2.5 micrometers.

In Table 4 and Table 5 estimation results are reported for emissions of each greenhouse gas and for different fine particle types emitted by vehicle flows moving inside the city. Absolute values and relative percentages are reported for each greenhouse gas, for two types of fine particles and for each vehicle category.

The entire transport system emits more than 127,000 tons of equivalent CO_2, 120,000 tons/year of CO_2, about 2,000 tons/year of CO, more than 4 tons/year of NO_2, more than 21 tons/year of methane and about 300 tons/year of VOC. Looking at each vehicle category, it can be easily seen that car transport emits the highest rate of CO_2 equivalent (about 45%), followed by goods vehicles (about 27%), bus (about 24%) and motorcycles (about 4%). As regards fine particle emissions (Table 5), 53 tons of PM10 fine particles are emitted in a year and it is interesting to note that 48 tons are PM2.5 particles.

The car, as expected, proves to be the transport mode which produces the highest rate of pollutants. It shows a percentage incidence always greater than 40% for each greenhouse gas, with peak values of 60% for carbon monoxide and 74% for nitrogen dioxide. As regards fine particles, car flows emit about 10 tons/year of PM2.5 (about 20%) and about 12 tons/year of PM10 (about 23%).

Motorcycles, though their negligible incidence on modal share, play a significant role as regards CO, CH_4/VOC and NM/VOC emissions. In fact, they emit more than 474 tons/year of CO (about 24%), more than 88 tons/year (about 29%) of VOC and more than 5 tons/year of CH_4/VOC (about 23%). The impacts on fine particle emissions are negligible. Indeed, motorcycle flows contribute less than 4% to PM2.5 and PM10 emissions.

Summing up emissions values for all the other transport modes (bus, heavy goods vehicles and light goods vehicles), it should be pointed out that they emit more than 55% of CO_2 and more than 50% of equivalent CO_2. Buses and heavy goods vehicles show similar emission percentages for all the considered greenhouse gases, light goods vehicles, due to their smaller modal share, show in some cases negligible emissions. From estimation results for fine particles buses and heavy goods vehicles emit more than 65% of PM2.5 (32 tons/year) and more than 60% of PM10 (34 tons/year). Unlike the case of greenhouse gas emissions, light goods vehicles play a significant role, accounting for 10% for both types of fine particles.

Starting from the values introduced above, two aggregate indicators were estimated: (1) emissions per capita, (2) ratio between emissions and GDP. Estimations showed that 1 ton of equivalent CO_2 and 0.38 kg of PM10 are produced by each resident, while 42 tons of equivalent CO_2 and 20 kg of PM10 are produced per million euros of GDP. Such values are smaller than those estimated for several Italian case studies.

Table 4: Salerno greenhouse gas emissions

	carbon dioxide	carbon monoxide	nitrogen dioxide	methane	other volatile organic compounds	equivalent carbon dioxide
vehicle category	**CO_2** (tons/year)	**CO** (tons/year)	**NO_2** (tons/year)	**CH_4 VOC** (tons/year)	**NM VOC** (tons/year)	***eq.CO₂*** (tons/year)
Car	53,229.07	1,166.68	3.11	10.19	131.25	57,206.13
Motorcycle	3,263.01	474.31	0.07	4.92	87.88	4.620.67
Bus	29,973.70	123.40	0.33	2.83	34.48	30,500.29
heavy goods vehicles	24,531.97	100.65	0.50	2.79	39.25	25,080.77
light goods vehicles	9,439.64	78.47	0.21	0.61	8.40	9,704.23
Total	**120,437.39**	**1,943.51**	**4.22**	**21.34**	**301.26**	**127,112.09**

vehicle category	**CO_2**	**CO**	**NO_2**	**CH_4 VOC**	**NM VOC**	***eq.CO₂***
Car	44.2%	60.0%	73.7%	47.8%	43.6%	45.0%
Motorcycle	2.7%	24.4%	1.7%	23.1%	29.2%	3.6%
Bus	24.9%	6.3%	7.8%	13.3%	11.4%	24.0%
heavy goods vehicles	20.4%	5.2%	11.8%	13.1%	13.0%	19.7%
light goods vehicles	7.8%	4.0%	5.0%	2.9%	2.8%	7.6%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Table 5: Salerno fine particle emissions

vehicle category	PM 2.5 (tons/year)	% PM 2.5	PM 10 (tons/year)	% PM 10
car	9,65	20,0%	12,12	22,8%
motorcycle	1,60	3,3%	1,78	3,4%
bus	16,92	35,1%	17,72	33,4%
heavy goods vehicles	15,24	31,6%	16,24	30,6%
light goods vehicles	4,82	10,0%	5,27	9,9%
total	**48,23**	**100,0%**	**53,13**	**100,0%**

4.3. Sensitivity analysis

The sensitivity analysis is proposed with respect to the main input variables and three different scenarios:

1) renewal of vehicle fleet,
2) modal shift from car mode to transit mode,
3) increase of average vehicle travel speeds.

If the first goal can be achieved assuming that part of EURO 0 and EURO 1 vehicles will be converted into EURO 4 and EURO 5 vehicles, the second goal can be achieved by implementing travel demand management policies pushing travel demand from private transport modes to the transit system and/or pulling travel demand towards the transit system. The third goal can be achieved reducing traffic congestion through modal shift strategies or simply making the supply network more efficient (increase in road capacity, optimization of road direction, signal setting optimization). For each scenario 10%, 20% and 30% percentage variations are hypothesized.

The analysis was developed through the methodology proposed. In the following tables, estimation results are reported in terms of fuel consumption and equivalent CO_2 emissions.

In Table 6 and Table 7 results are reported for different percentages of vehicle fleet renewal. As regards fuel consumption, benefits vary from -1% with a conversion rate of 10% to -4% with a conversion rate of 30%. A similar trend can be observed for CO_2 equivalent emissions, whereas significant reductions can be obtained for PM10 emissions: -14% with a conversion rate of 10% , -37% with a conversion rate of 30%. These results may be achieved thanks to efficient anti-fine particle filters equipped the new vehicles.

Table 6: Salerno traffic fuel consumption with respect to vehicle fleet renewal

% of vehicle fleet renewal	gasoline consumption (tons)	diesel consumption (tons)	% var. gasoline consumption	% var. diesel consumption	total consumption (pet)	% var. total consumption
0%	11,643	26,684	0.0%	0.0%	42,790	0.0%
10%	11,547	26,244	-0.8%	-1.7%	42,200	-1.4%
20%	11,452	25,758	-1.6%	-3.5%	41,560	-2.9%
30%	11,360	25,413	-2.4%	-4.8%	41,078	-4.0%

Table 7: Salerno traffic emissions with respect to vehicle fleet renewal

% of vehicle fleet renewal	eq.CO2 (tons/year)	% var. eq.CO2	PM 10 (tons/year)	% var. PM 10
0%	127.130	0.0%	53,1	0.0%
10%	124.095	-2.4%	45,5	-14.3%
20%	120.912	-4.9%	39,1	-26.4%
30%	119.016	-6.4%	33,4	-37.1%

Better results on fuel consumption and greenhouse gas emissions may be achieved on driving users from cars to the transit system (Table 8). Having set three modal shift scenarios (car: -10%, -20%, -30%), fuel consumption and equivalent CO_2 emissions decrease almost constantly, while PM10 emissions do not observe a significant variation. Hypothesizing a 30% modal shift from car to transit, a 10% reduction in fuel consumption and CO_2 equivalent emission can be obtained and only a 2% reduction in PM10 emissions.

Such results can be greatly enhanced if we consider that a modal shift, reducing traffic congestion, may increase vehicle speed, allowing benefits in terms of consumption and emissions. In Table 9, a parametric analysis is proposed with respect to three scenarios: 10%, 20% and 30% increase in average vehicle speed. Results show a percentage decrease ranging from 5% up to 13%, as with fuel consumption, CO_2 equivalent emissions and PM10 emissions. Such results, if combined with the results shown for modal shift, show that a transportation policy which is able to change modal split and reduce vehicle speed at the same time, allows the effects on consumption and emissions to be doubled.

In conclusion, PM10 emissions can be abated only through policies based on the renewal of the vehicle fleet, while emissions and fuel consumption require transportation policies aimed at reducing car use and increasing vehicle speed on the network.

Table 8: Modal shift from car mode to transit mode: effects in terms of traffic fuel consumption and emissions

% variation of trips		total consumption (pet)	% var. total consumption	eq.CO2 (tons/year)	% var. eq.CO2	PM 10 (tons/year)	% var. PM 10
car model	**transit mode**						
0%	**0%**	42,790	0.0%	127,130	0.0%	53.1	0.0%
-10%	**+10%**	41,309	-3.5%	122,941	-3.3%	52.8	-0.6%
-20%	**+20%**	39,828	-6.9%	118,752	-6.6%	52.5	-1.2%
-30%	**+30%**	38,338	-10.4%	114,539	-9.9%	52.2	-1.8%

Table 9: Average vehicle travel speed variations: effects in terms of traffic fuel consumption

% variation of vehicle speeds	gasoline consumption (tons)	diesel consumption (tons)	% var. gasoline consumption	% var. diesel consumption	total consumption (pet)	% var. total consumption
0%	11,643	26,684	0.0%	0.0%	42,790	0.0%
10%	11,097	25,419	-4.7%	-4.7%	40,768	-4.7%
20%	10,628	24,287	-8.7%	-9.0%	38,983	-8.7%
30%	10,210	23,264	-12.3%	-12.8%	37,377	-12.9%

Table 10: Average vehicle travel speed variations: effects in terms of traffic emissions

% variation in vehicle speeds	**eq.CO2 (tons/year)**	**% var. eq.CO2**	**PM 10 (tons/year)**	**% var. PM 10**
0%	127,130	0.0%	53.1	0.0%
10%	121,096	-4.7%	50.6	-4.8%
20%	115,905	-8.8%	48.4	-9.0%
30%	111.234	-12.5%	46.4	-12.7%

5. Conclusions

Today, transport energy consumption and emissions account for about 20%-40% of the total. In such a context, good estimation of transport impacts should be envisaged and strategies/policies for their mitigation proposed. Recently the Urban Energy Plan (UEP) was introduced as a fundamental characteristic of urban planning activities. The UEP is a strategic plan which aims to reduce energy consumption and pollutant emissions produced by several sectors.

With respect to this aim, in this paper a method to estimate traffic fuel consumption and emissions at urban scale was proposed. The aim was to estimate global performance indicators by integrating transportation models with fuel consumption and emission models. The innovative elements of the proposed methodology were:

- disaggregated estimation of the input variables;
- disaggregated estimation of travel demand by vehicle type;
- estimation of a model able to quantify the effect of some transport system modification in terms of vehicle consumption and emission variations; this allows impacts to be estimated with respect to hypothetical design scenarios.

The methodology was applied to the city of Salerno (Italy) and is part of the actual UEP. It is based on consolidated methods/models of transportation system analysis. As regards the estimation of fuel consumption and emissions, the European approach based on the COPERT method was pursued.

A sensitivity analysis was proposed with respect to three different hypotheses: renewal of the vehicle fleet, modal shift from car mode to transit mode and reduction in traffic congestion. Simulation results highlight that a transportation policy which is able to change modal split and reduce vehicle speed at the same time, allow the effects on consumption and emissions to be doubled. Furthermore, fine particle emissions can be abated only through policies based on the vehicle fleet renewal, while emissions and fuel consumption require transportation policies aimed at reducing car use and increasing vehicle speed on the network.

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