INTEGRATION OF A GEOGRAPHIC INFORMATION SYSTEM IN A TRANSPORT EXTERNALITIES ASSESSEMENT TOOL

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1. INTRODUCTION

The massive and continuously growing scale of the transportation system causes significant impacts from congestion, air pollution, noise, accidents and resource depletion, which impose extra costs on society and individuals. Such costs, imposed to a group of persons by the social or economic activities of another group of persons, without taking into account the effects of his activity in their decision making process, are considered to be external. The existence of significant external costs or benefits generally results into an economically inefficient use of resources and could justify or require public policy actions, in order to correct these market failures [1].

Some of the most important externalities of transport are those associated with environmental and health damages caused by air pollution. Literature reviews of studies estimating the environmental damages of air pollution in Europe and the United States are presented by Krupnick [2] and Verhoef [3]. A detailed approach for the assessment of environmental externalities was introduced in the ExternE project [4] for all fuel cycles of electricity generation. Mayeres [5], used the results of the ExternE project to estimate the externalities of transport. However, the extrapolation of results for electricity generation in the assessment of transport externalities is of questionable accuracy due to the following reasons: (a) transport activities do not produce the same pollutants as electricity generation and the impacts caused are different, (b) the pollutants are emitted from linear (roads) instead of point sources (stacks), (c) the pollutants produced by electricity generation are usually emitted from stacks and are well dispersed while the pollutants produced by transport activities are emitted in low heights and mainly affect neighbouring areas and (d) the areas around power plants are usually not densely populated while a large proportion of transport occurs within cities.

A methodology for the quantification of energy-related environmental externalities of transport, taking into account all the above-mentioned particularities, is being developed within the framework of the ExternE-Transport project [6]. This methodology was applied to a number of case studies in different European countries. The results from these studies show a wide variety in damage estimates depending on the transport mode, the fuel used, the pollution control technology of the vehicle, the vehicle's operating mode, as well as on factors depending on the location of the transport task, such as population density and distribution, and atmospheric conditions (wind speed, wind direction, atmospheric stability). The site-dependence of air pollution-transport externalities and the need to reveal their relation to specific geographical characteristics, such as the spatial relationship between the emitter and the receptors of pollution, dictates the need for the development of a computer tool operating under a G.I.S. platform.

In the present work, "Ecosense" [7], a computer tool for the assessment of the air pollution induced externalities of electricity generation, was modified in order to calculate the environmental cost of road transport. New modules operating within a G.I.S. environment were developed for the determination of road geometry, location and traffic conditions, the calculation of atmospheric pollutant emissions and the assessment of local impacts, taking into account location specific variables such as meteorology and population distribution and density. The computer tool's results can be utilised in the analysis and the comparative assessment of policies aiming to reduce the environmental impacts of transport with area-specific measures, the determination of economically justified pollution abatement and the development of environmental performance indices for the various pollution control technologies.

2. SYSTEM DESIGN

2.1. Methodology

The aim of the ExternE Transport project was to modify and extend the methodology, already developed for the assessment of energy related marginal environmental externalities of the various fuel cycles of electricity generation, in order to quantify the corresponding damages of the transport sector. The impacts and the corresponding costs resulting from the use of transport means were assessed using the "impact pathway approach" [4]. The impact pathway delineates the linkages between a burden and some health or environmental endpoint. The principal stages of the impact pathway approach are:

(a) Identification of the polluting activity: Characterisation of the polluting activity. Features such as, location, technology used and operating parameters, are identified.
(b) Quantification of burdens: Quantification of pollutant emissions using appropriate models.
(c) Description of the receiving environment: The receptors' density and distribution within the analysis boundary, as well as meteorological conditions affecting the dispersion and chemistry of the atmospheric pollutants are identified.
(d) Quantification of exposure: Calculation of incremental concentration of pollutants over the affected area using appropriate dispersion models, and assessment of receptors' exposure.
(e) Quantification of impacts: Estimation of physical impacts using exposure response functions

(f) Valuation of impacts: Estimation of the incremental external cost of the activity using specific values for each impact category.

The use of the above stated methodology provides the external cost due to the incremental impacts of a polluting activity at a specific site. Correctly accounting for site dependence, both of sources and receptors, is a distinguishing feature of this approach.

2.2. System analysis

The tool development was based on “Ecosense”, the existing tool for the assessment of the air pollution induced external cost of electricity generation. The new modules developed operate under a G.I.S. environment with the objective to exploit its powerful features in handling complex road geometry, location specific parameters (receptors’ density, meteorological characteristics), and to reveal the spatial relation between location of transport activity and the resulting externalities. G.I.S. environments handle geographical entities, attributes defining their characteristics and methods determining their behaviour and interaction. These geographical entities are represented as point, line or polygon objects. Attributes are stored as database records and are referenced to the corresponding geographical objects. Methods can be categorised to those handling geographic operations and to those handling database operations. Built-in functions are used to create, store and retrieve objects.

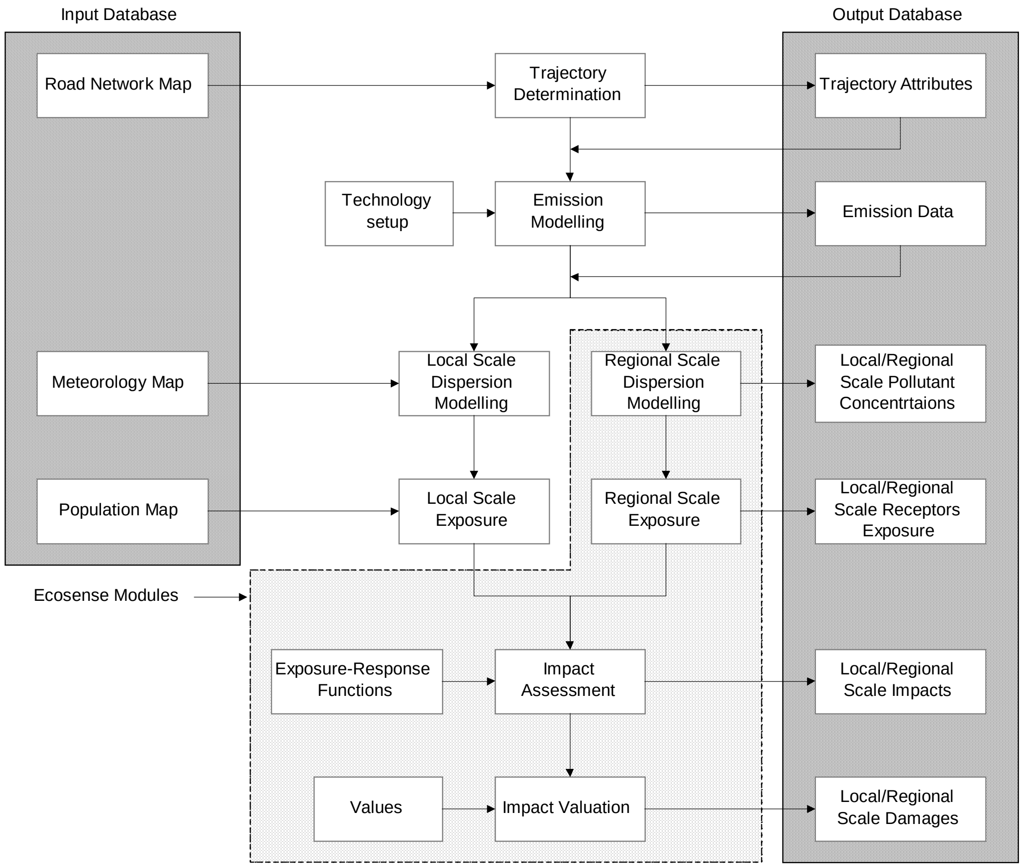


Figure 1: Tool structure

The tool structure for the assessment of the air pollution impacts and externalities is presented in Figure 1. The evaluation procedure follows the steps of the impact pathway approach. The extension of "Ecosense" concerns the stages of transport task determination, emission modelling, and dispersion modelling and exposure assessment on local scale (up to 20 km from the emission source).

The database structure was designed on the basis of the input needed by the models and the obtained results of each stage of the methodology. G.I.S. represents database tables as separate map layers. Data exchange between different layers is performed using geographic or database operations. The map layers, the data flow and the methods used are presented in Figure 2. The trajectory layer objects are copied from the road network layer and their attributes are inherited from the road network layer or are user-defined. The trajectory attributes data are used as input for emissions modelling. The grid generation procedure uses the trajectory's geometry to create the receptors' grid. The trajectory's geometry and attributes are also used as input data for dispersion modelling. The pollutant concentrations are calculated in each cell of the grid, producing the concentration layer. The pollutant concentrations are combined with population data from the receiving environment layer using special geographic functions (as these two layers refer to different geographic objects), calculating the receptors' exposure.

The following paragraphs describe the calculation procedure of each stage as well as the geographic objects, attributes and methods used.

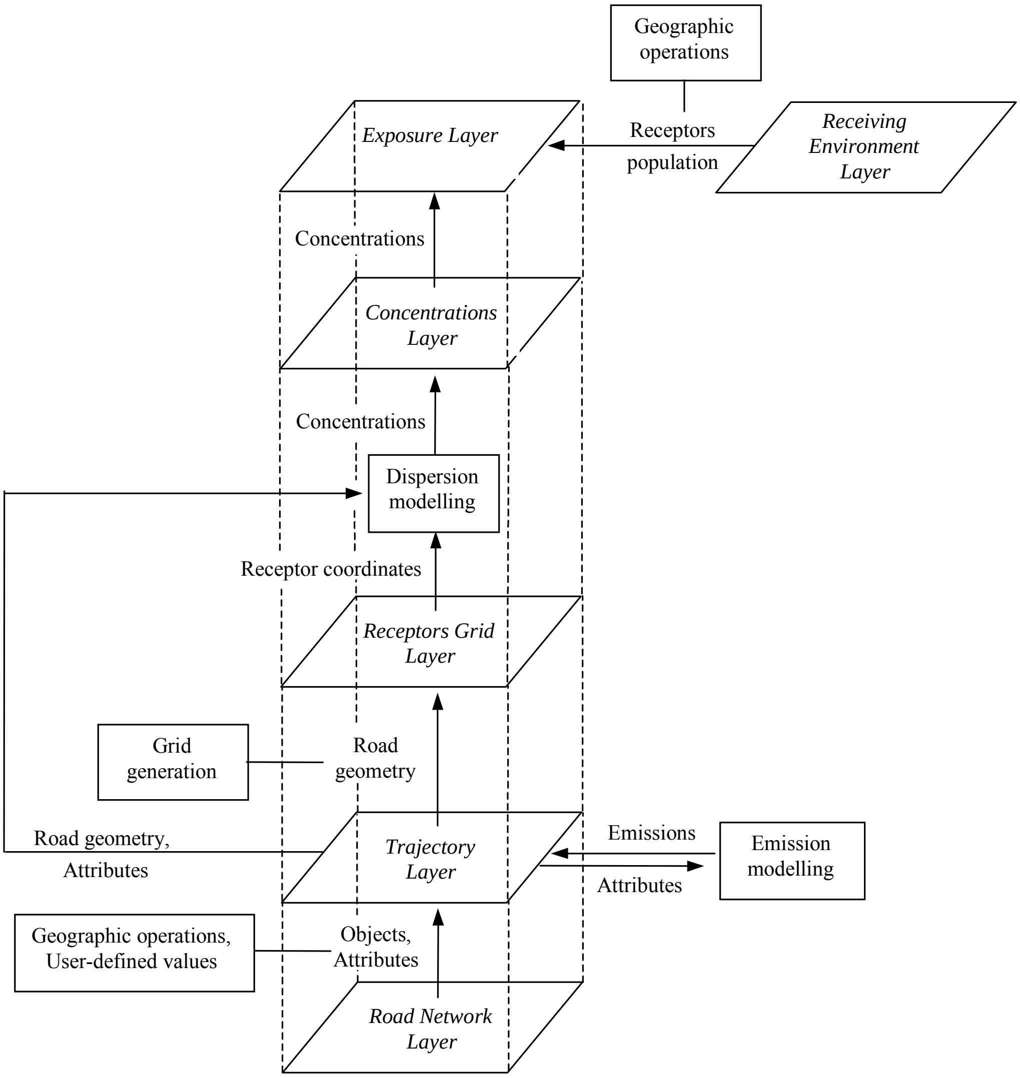


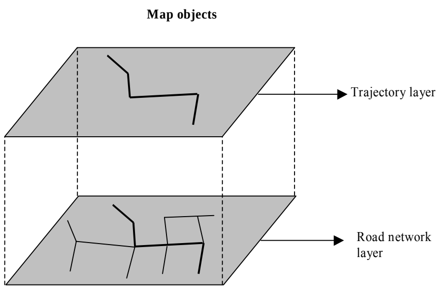
Figure 2: Data flow between G.I.S. layers

2.3. Transport task database

2.4. Trajectory setup module

The location of transport activities significantly influences the resulting environmental impacts. The trajectory determination module operates within G.I.S. environment and provides appropriate functions for the identification of the location, geometry and attributes of the transport task's route. All operations are based on the use of a map representing a transport mode's network. The geographical objects of this map consist of lines corresponding to the roads of the transport network.

The trajectory of each transport task examined is defined as a subset of the entire network. Special functions are provided for the selection and editing of the objects composing the trajectory. Additional attributes are used, in order to host the location, geometry and traffic data of the trajectory segments. G.I.S. provides built-in methods for the identification of each object's co-ordinates and geometry (e.g. if it consists of more than one linear segments), as well as for the calculation of their length. The traffic data of the trajectory segments are either inherited from the original objects of the transport network map, or can be user-defined (Figure 3). A set of geographical operations, allowing to merge a number of trajectory objects, or to split an object into two or more segments, is also provided. The attributes values of an object resulting from merging operations can be estimated either by summing the values of the original objects (e.g. the merged object's length, is equal to the sum of the original objects lengths), or by calculating the weighted average of the original objects attribute values. In the case of splitting objects, the resulting road segments inherit the attribute values of the original object.



Attributes

ID	Length	Traffic speed	Slope
1	1250	50	0
2	983	40	-1

ID	Name	Traffic speed	No of lanes per direction	Road Type
1	Λεωφόρος Διονύσου	50	2	Principal
2	Ρήγα Φεραίου	40	1	Secondary
3	Λεωφόρος Θησέως	60	2	Principal

Figure 3: Data exchange between road network and trajectory map layers

The result of this step is a set of attributes corresponding to geographical objects, which are stored in the trajectory attributes database. The values of these attributes can be retrieved from the database and used as input for emission and dispersion modelling at the next steps of the impact pathway.

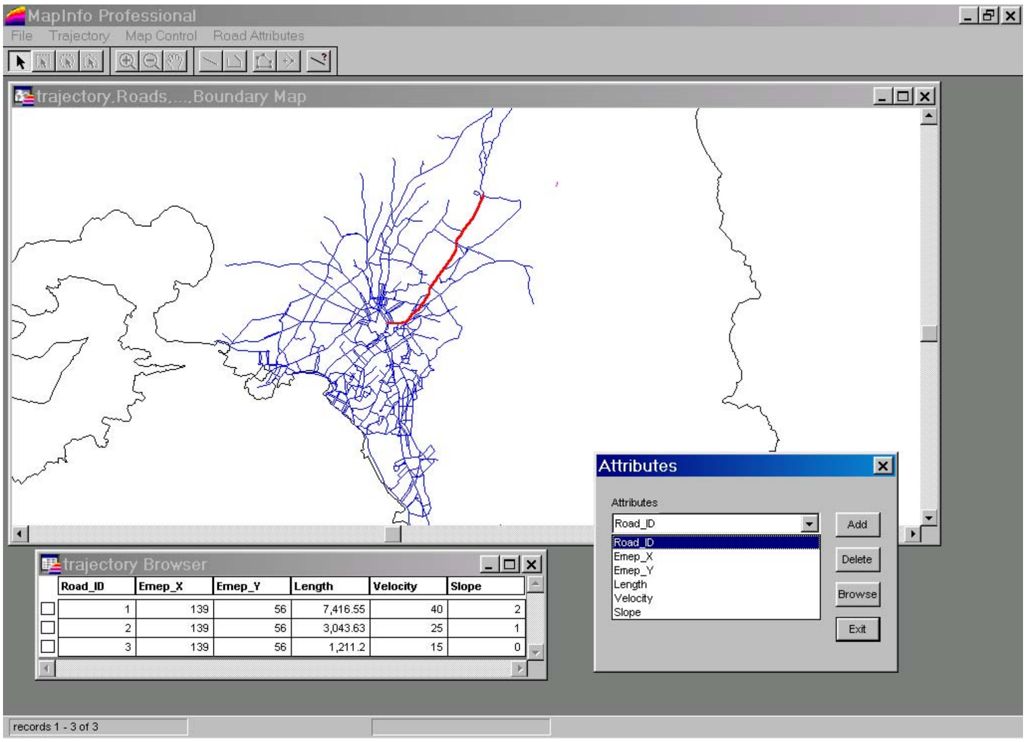


Figure 4: User-interface of the trajectory setup module

2.5. Emission modelling module

2.6. Local scale analysis module

The local population exposure to the various pollutants is calculated in the local scale analysis module. G.I.S. provides built-in geographical operations that identify the relative geographical location of the pollutant concentration and the population density profiles. The G.I.S. is also used to present the geographic allocation of population exposure.

In the first step of the local scale analysis, a grid for the calculation of pollutant concentrations is generated. The resulting grid has variable cell density in order to get more accurate results from the dispersion modelling without increasing excessively the computing time. More specifically the grid is denser close to the source, where the concentration gradient is steeper than away from the source. Buffer zones around the transport task trajectory define the areas having grid cell size ranging between 125m and 2000m. The grid cells are represented as area objects within the G.I.S. The centroid co-ordinates of the grid cells are used as input for the dispersion model, representing the receptor co-ordinates.

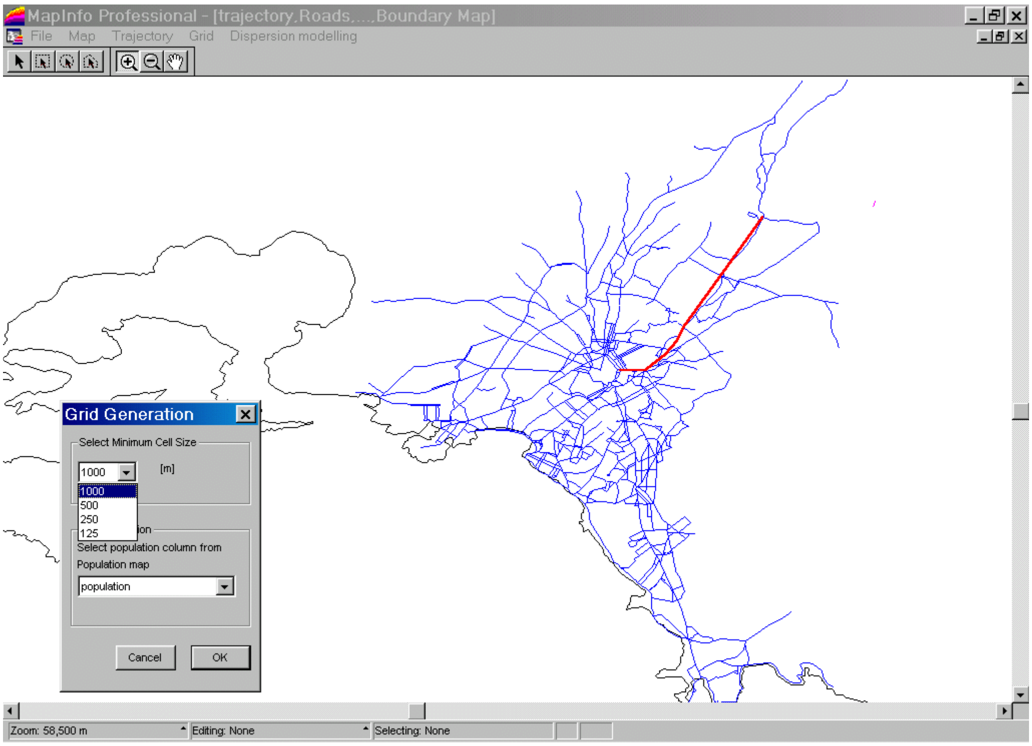


Figure 5: Local scale analysis module - grid generation parameters

A gaussian line source dispersion model has been implemented within the G.I.S. environment. This model predicts the annual average pollutant concentrations in a range of up to 20 km away from the source using as input data the road geometry, the pollutant emissions, the receptors co-ordinates, as well as meteorological data. The road geometry data are retrieved from the trajectory attributes database. A meteorology map identifying areas of similar climatological conditions and containing data on wind speed, wind direction and atmospheric stability frequencies of occurrence, provides the meteorological data needed for dispersion modelling. The basis of the model is the Gaussian plume equation, mainly used to model point source emissions from stacks [8]. The line source model is based on a numerical integration over the line source of the Gaussian point source plume formula [9]. Four different methods, depending on the surface roughness of the area examined and on vehicle induced turbulence, for the calculation of vertical dispersion coefficients are implemented in the model. More specifically, the methods available are (a) the Pasquill-Gifford curves [9], (b) the Briggs formulas for urban areas [9], [10], (c) the Briggs formulas for rural areas [9] and (d) the Benson equations [11].

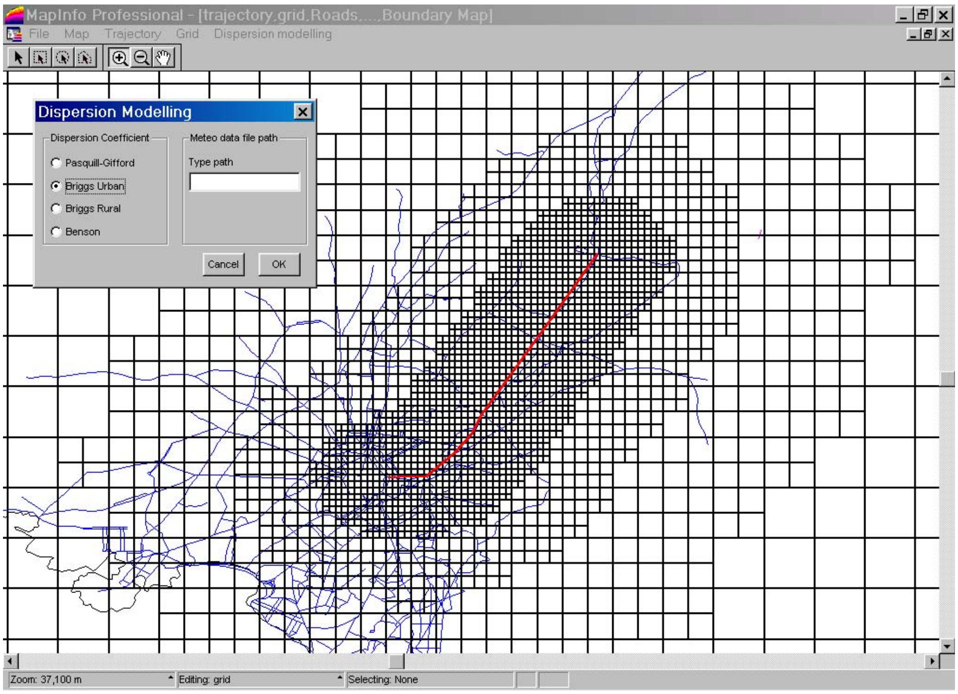


Figure 6: Local scale analysis module – dispersion modelling parameters

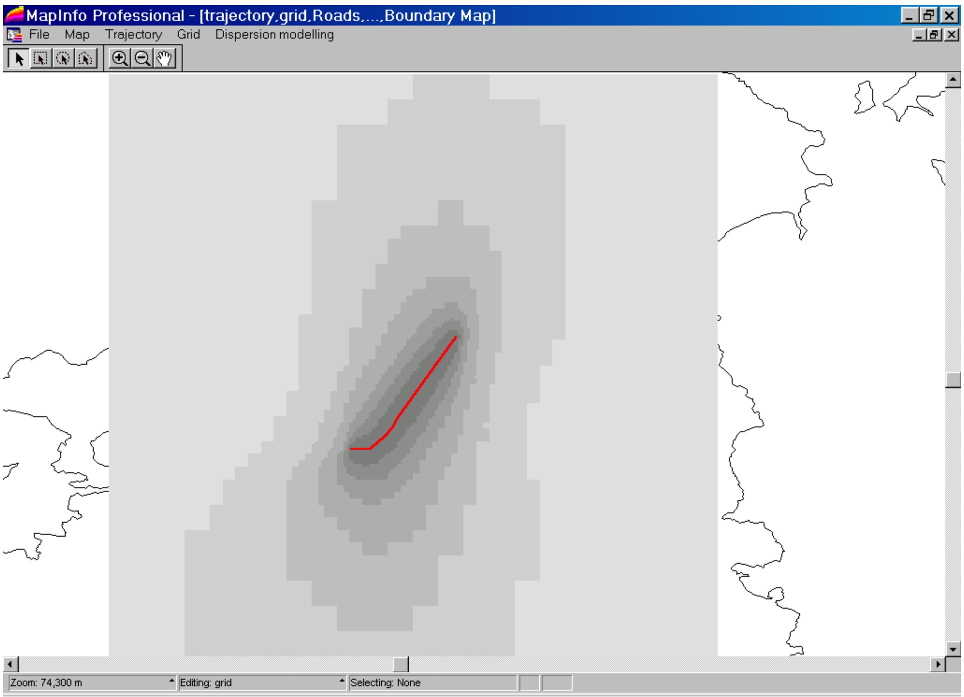


Figure 7: Local scale analysis module – pollutant concentration profile

The annual average concentrations of the pollutants, in each cell of the receptors' grid are calculated using the dispersion model. The annual average population exposure to the pollutants is then estimated using a map representing the population allocation in the area. The exposure estimation is performed by geographic operations that provide the relative geographical location of the area objects of the population map and the grid cells, and the use of the following equation for each object of the population map:

$$E_j = C_j \cdot \sum_{i=1}^{n} \frac{P_i \cdot A_{i,j}}{A_i}$$

where: E_j = the population exposure of the j^{th} grid cell
C_j = the population cell
n = the number of objects of the population map intersecting the j^{th} grid cell
P_i = the population of the i^{th} object of the population map
$A_{i,j}$ = the area of the i^{th} object of the population map overlapping the j^{th} grid cell
A_i = the area of the i^{th} object of the population map

The results are stored in a database for future reference and for further use at the impact assessment procedure.

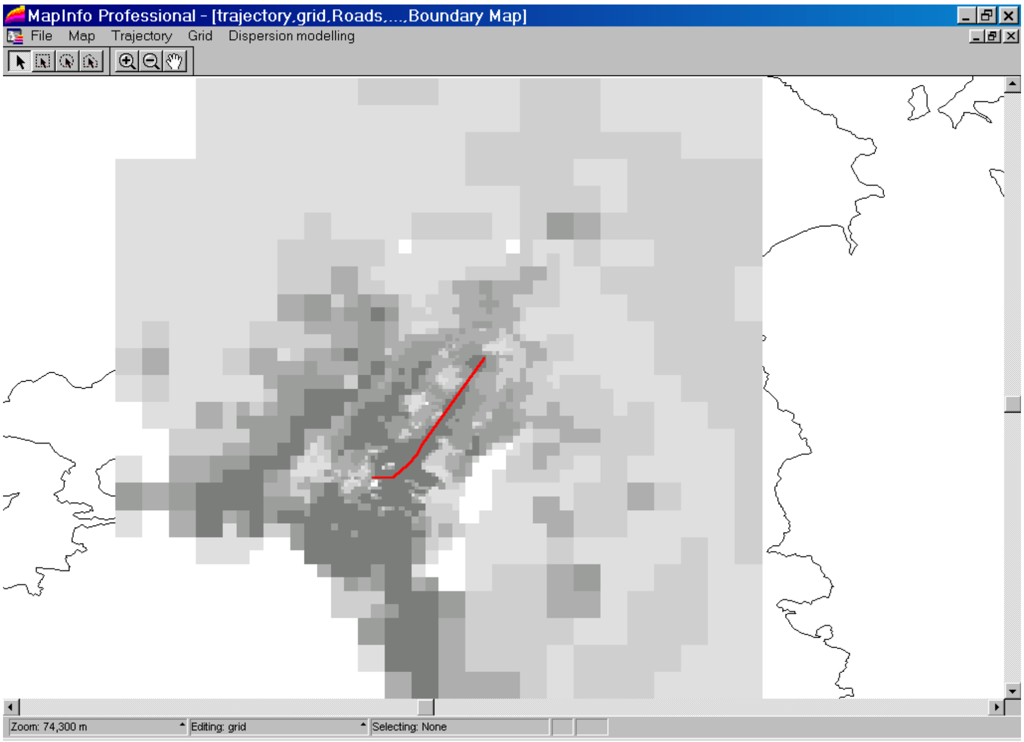


Figure 8: Local scale analysis module – exposure profile

3. CONCLUDING REMARKS

The integration of G.I.S. in a transport externalities assessment tool, presented in this in work, allows handling of complex road geometry and identifies the allocation of receptors in respect to pollutant concentrations. The adoption of G.I.S. provides a spatial insight on the results, revealing the relation between the emitter and the receptors of the pollution. The tool also distinguishes between different transport modes and technologies, producing mode-technology-location specific results.

The mode-technology-location combinations are the "building blocks" [12], that is the structural elements for the analysis of the externalities introduced by any transportation system. The use of building blocks allows for identifying a common aggregation level for the assessment of transport externalities. The differentiation between transport modes, technologies used and locations, produces results that assist decision-makers to internalise the impacts of transport, using various policy instruments such as vehicle, fuel and road taxes, modal shifting and traffic constraints. The internalisation of transport impacts, as a result of accurate transport pricing, is a key element for sustainable transport systems.

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