The study of traffic flow on selected road network in Cracow

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Abstract: The paper describes the work involved in a large research project, the aim of which is estimated emissions in the Cracow agglomeration. The project envisages the identification of emission sources as well periodically change it during the year, the month and the time of day. The results of the research presented in this paper concern only preliminary estimation of traffic flows at selected points of road network of urban agglomeration. The research methodology has been developed to meet the requirements of the developed model, which takes into account the different types of sections of the Krakow road network, different time of day, different days of the week and, most importantly, different types of vehicles together with their emission categories. For practical reasons, a number of simplifications have been made, the more important of which are the merging of certain emission categories and the adoption of the average speed of movement of vehicles on the test section. The measurements were carried out by a group of about 150 trained specialists from the so called - ‘car’, with knowledge of the issues of vehicle identification in terms of emission of toxic components of exhaust gases. The measurement results will be inputs to the overall pollutant emission model.

1. Introduction
The work relates to the identification of traffic flow in the urban area, taking into account its categorization toxic exhaust emissions. The study was performed as part of an integrated project called LIFE: "Implementation of the Program of air protection in Lesser Poland province – Malopolska in a healthy atmosphere". They constitute one of the components necessary for modelling the emission transport in Cracow. The scope of the work carried out in the Cracow University of Technology included, among others, field tests measure traffic within the administrative boundaries of the Municipality of Cracow. These studies were conducted on selected days of the week during the peak morning and during the afternoon rush, as well as a day off from work on selected streets, in the same hours.
Due to the limitations of the method used, the measurement system has been developed to identify the vehicles that are compatible with this measurement and guaranteed to get results with the required accuracy. For this purpose, a simplified system for vehicle identification based on COPERT system was introduced. The applied division, in which the selected groups of vehicles were combined, takes into account the specifics of the domestic car fleet, including the participation of the vehicles with a great degree of exploitation or the ones with the after treatment system removed in traffic.
The measuring team was a group of 150 special trained students of the Faculty of Mechanical Engineering of Technical University of Cracow. The measurements of stream traffic were held at 36 typical streets of the road network of the Municipality of Cracow, including: highway, main street, main street with accelerated motion, principal street with tram track, principal street with the tracks in the median strip, a local street with tram track, collective street and cumulative street with tracks in the road.
2. Aim and scope of work
The work were done in the integrated project LIFE entitled: “Implementation of the Program of air protection in Lesser Poland province – Malopolska in a healthy atmosphere” is to be one of the component elements, necessary to the planned study of the software for modelling of communication emissions in Cracow, within the realization of the objective project. The scope of work realized by Cracow University of Technology included:
1) Preparation works – training of the people taking the measurement,
2) Field measurement research aiming at defining the category of exhaust gas emission of the particular groups of vehicles moving of the streets of Cracow, together with counting the average speed of movement of the vehicles,
3) Processing of the direct results of the research and preparing the final report.
Territorial scope of the research: Municipity of Cracow in the territorial borders.
The field measurement research were carried out on November 15 (Tuesday) and November 17 (Thursday) 2016 during the morning rush hour (7:00-7:30 a.m. and 8:00-8:30 a.m.) and during the afternoon rush hour (3:00-3:30 p.m. and 4:30-5:00 p.m.), according to the localization of the measurement points that is shown by fig.1. On Sunday – November 20, 2016, on the chosen streets, show on fig.2, the measurement was done between the hours: 10:00-10:30 a.m. and 11:00-11:30 a.m., as well as 5:00-5:30 p.m. and 6:00-6:30 p.m.

3. Description of the methods of carryout of the research
3.1. Limitations of the exhaust gas emission
New car vehicles admitted to the traffic for the first time must meet specific homologation requirements, of which the most important role play the regulations of permissible size of emission of toxic components of exhaust gas. The limitations that are now in force in Europe for the vehicles of the permissible gross weight up to 3,5 tons are verified during the road cycle (NEDC), simulated on the chassis dynamometer. For the vehicles above the weight of 3,5 tons the meeting of the limitations of the emission is tested during the realization of certain tests, which the engines of these vehicles undergo on the chassis dynamometer (ESC, ELR, ETC tests).
Enforcement of the specific limitations of emission is specified with the date from which all of the vehicles brought into production for the first time must meet the given terms. Other vehicles, that got the homologation certificate before the date of the introduction of the given limitation, can be produced without any change for another year, in which they should be adapted to the new limitation of
emission. Also, the already produced vehicles that did not find the purchasers can be sold in the following years on the basis of the individual admissions.

This way of enforcement of the following limitations of emission does not allow the unambiguous determination of the date from which all of the produced vehicles will meet one limitation. In relation to the above, using the data about the emission defined on the basis of the date of admission of the vehicle to the traffic for the calculation models is burdened with certain error.

3.2. Calculation models of emission of exhaust gas components

In the European Union countries, the first work on establishing a system for the definition and calculation of emissions of toxic substances in air was made in 1985 by means of establishing the CORINAIR (Coordination d’Information Environmental) program by the European Agency for Environment Protection. Within these works, COPERT program was established, the aim of which was collecting data and forecasting the emission of toxic components of exhaust gas from road traffic. This system was purposely worked out by a specifically called on group of specialists from the European Union (Corinair Working Group on Emission Factor for Calculating Emission from Road Traffic).

Usually COPERT program can be used for calculating the communication emission coming from different types of road network. It also takes into consideration different cases of exploitation of vehicles: so called hot emissions from the vehicles in movement, where it is concluded that the engine is heated and works optimally, as well as cold-start emissions showing during the start-up and heating of the engine. What is taken into consideration in the model and program is a big share of this part of the emission particularly in the winter period, when the air temperature is low, which causes problems with the start-up of the engine. The last group is the evaporation emission of different types of volatile hydrocarbons, showing during the exploitation of vehicles.

COPERT program [2] is kept being actualized and recently, its fifth version is already available, as well as another actualization 5.0 1067 published in October 2016.

What is included in this program is a very detailed division of vehicles, parameters influencing the quality of emission included. The system includes all the needed parameters and allows their direct, comfortable transfer to the general program of emission forecasting CORINAIR [3,4]. The factors determining the membership of a vehicle to the given group are among other things: size and kind of the vehicle and engine, construction characteristics influencing the size of emission, kind of norm concerning the toxicity and being in force at the time of admission of the vehicle to the traffic, area of usage of the given vehicle, as well as scope and way of carrying out the periodical emission tests.

The reliability of the results of emission is greatly determined by the contents of databases considering the car park, yearly run of the vehicles, whole amount of used fuel, or considering the road networks in each country taking part in the project.

The general classification used in COPERT system considers following groups of vehicles:

- **Group I** – passenger cars with SI engines (spark engines) with displacement volume $V_{SS} < 1.4 \text{ dm}^3$,
- **Group II** – passenger cars with SI engines with displacement volume $1.4 \text{ dm}^3 < V_{SS} < 2.0 \text{ dm}^3$,
- **Group III** – passenger cars with SI engines with displacement volume $V_{SS} > 2.0 \text{ dm}^3$,
- **Group IV** – passenger cars with CI engines
  - a) with displacement volume $V_{SS} < 2.0 \text{ dm}^3$,
  - b) with displacement volume $V_{SS} > 2.0 \text{ dm}^3$,
- **Group V** – passenger cars with engines powered by propane-butane gas (LPG).
- **Group VI** – passenger cars with 2-stroke SI engines
- **Group VII** – trucks i microbuses with permissible gross weight up to 3,5 tons:
  - a) with SI engines,
  - b) with CI engines.
- **Group VIII** – Trucks and buses:
  - a) with permissible gross weight bigger than 3,5 tons and with SI engines,
  - b) with permissible gross weight from 3,5 tons to 16 tons and with CI engines,
  - c) with permissible gross weight bigger than 16 tons and with CI engines.
Group IX – motorcycles:
   a) with engines with displacement volume $V_{SS} < 50 \text{ cm}^3$,
   b) with 2-stroke SI engines with displacement volume $V_{SS} > 50 \text{ cm}^3$,
   c) with 4-stroke SI engines with displacement volume $V_{SS} > 50 \text{ cm}^3$.

Group X – all-terrain vehicles used in:
   a) agriculture,
   b) forestry,
   c) industry,
   d) army.

Each of the groups of vehicles is connected to a category of emission, which results from the homologation regulations. For stage, below emission categories considering the passenger cars with spark engines are shown:
   a) from the period before the enforcement of ECE forms, vehicles produced up to 1971,
   b) ECE 15/00 and ECE 15/01 norms, vehicles produced in 1972-1977,
   c) ECE 15/02 norms, vehicles produced in 1978-1980,
   d) ECE 15/03 norms, vehicles produced in 1981-1985,
   e) ECE 15/04 norms, vehicles produced in 1985-1992,
   f) for engines with reduced emission, produced in 1985-1986,
   g) for vehicles with 3-way catalytic convertor working in open loop without $\lambda$ sensor, vehicles produced in 1985-1992,
   h) EURO I – vehicles produced in 1992-1996,
   i) EURO II – vehicles produced in 1996-2000,
   j) EURO III – vehicles produced in 2000-2005,
   k) EURO IV – vehicles produced in 2005-2009,
   l) EURO V – vehicles produced in 2009-2013,
   m) EURO VI – vehicles produced from 2014 onwards.

Program COPERT system is kept being verified and improved. For the biggest group of vehicles, which is undoubtedly passenger cars, the emission of exhaust gases, that is CO, CH, NO$_X$ and PM solid particles is currently written in polynomials, allowing calculation of emission in g/km in the function of average speed of movement of the vehicle. In the previous years, steady numbers were used determining the size of emission for the city and suburban traffic, as well as traffic on the highway. This way is still used in consideration of the other groups of vehicles. Also, functions were worked out to show the average usage of fuel in relationship to the speed or the steady number is given, characteristic for the given type of traffic.

The given formulas defining the factors of emission are kept being verified, considering the changes in the vehicle technology and road traffic conditions by that, making the topic of factors of emission still actual. The precision of the obtained end result is most dependent on the numbers of independent parameters used in the calculation program, and considering the car park and road traffic.

3.3. Assumptions established in the carried out measurements

Due to the series of limitations concerning the realized project, a series of assumptions were established, allowing the carryout the given tasks.

The first Assumption was choosing the place and time of carrying out the measurements of flows of traffic in the traffic network of Cracow. According to the directives of the ordered, the measurements were taken in the appointed points of city of Cracow and considering different characteristics of the road traffic on the chosen fragments of the roads. By that, every type and kind of the roads occurring in Cracow was taken into consideration, both when it comes to the building of the road and the heaviness of traffic, so that the results could become a basis to estimating the size and characteristics of the road in the whole area of the city.

The measurements were taken on the 2 chosen work days (Tuesday, November 15, and Thursday, November 17, 2016) and on Sunday, November 2016.
The measurements were taken during the morning rush hour (7:00-7:30 a.m. and 8:00-8:30 a.m.) and during the afternoon rush hour (3:00-3:30 p.m. and 4:30-5:00 p.m.). Due to the limitation coming from the chosen measurement method, a vehicle identification system was worked out, corresponding to the measuring possibilities and guaranteed meeting the results of the needed precision. For this purpose, a simplified vehicle identification system was established, considering the following groups of vehicles:

- **Group I** – passenger cars with SI engines, produced before 1992, corresponding to the category of emission before the establishment of Euro norms, suggested establishment of factors like for Euro 0,
- **Group II** – passenger cars with SI engines, produced in 1992-2009, corresponding to the category of emission Euro 1, Euro 2, Euro 3, and Euro 4, suggested establishment of factors like for Euro 3,
- **Group III** – passenger cars with SI engines, produced from 2010 on, corresponding to the category Euro 5 i Euro 6, suggested establishment of factors like for Euro 5,
- **Group VI** – passenger cars with CI engines produced before 1992, corresponding to the category of emission before the establishment of Euro norms, suggested establishment of factors like for Euro 0.
- **Group V** – passenger cars with CI engines produced in 1992-2009, corresponding to the category of emission Euro 1, Euro 2, Euro 3, and Euro 4, suggested establishment of factors like for Euro 3,
- **Group VI** – passenger cars with CI engines, produced from 2010 on, corresponding to the category Euro 5 i Euro 6, suggested establishment of factors like for Euro 5,
- **Group VII** – goods carrying cars and buses produced to 2009, corresponding to the emission norm before establishment of Euro 0–Euro 4 norms, it is assumed that these have engines without the filter of solid particles, suggested establishment of factors like for Euro 3,
- **Group VIII** – goods carrying cars and buses produced from 2010, corresponding to the category Euro 5 i Euro 6, it is assumed that these have engines with the filter of solid particles, suggested establishment of factors like for Euro 5,
- **Group IX** – trucks and buses produced to 2009, corresponding to the emission norm before establishment of Euro 0–Euro 4 norms, it is assumed that these have engines without the filter of solid particles, suggested establishment of factors like for Euro 3,
- **Group X** – trucks and buses produced from 2010, corresponding to the category Euro 5 i Euro 6, it is assumed that these have engines with the filter of solid particles, suggested establishment of factors like for Euro 5,

The shown division, in which the chosen groups of vehicles were connected, considers the characteristics of the national car park, in that participation in the road traffic of the vehicles of the great exploitation level or vehicles with the exhaust gas cleaning systems removed. In some cases the groups were connected because of the numbers of emission of the toxic components of exhaust gas being very similar, like for example goods carrying cars and buses or trucks and buses. The rest of the groups shown in the COPERT classification were omitted due to their small amount and rare occurrence in the traffic in Cracow. This includes motorcycles and motorbikes, which are usually not used in the period of carrying out the measurements (winter period).

### 3.4. Method of measurement

The members of the measuring groups were the students of Mechanical Department of Cracow University of Technology, having the technical knowledge necessary for carrying out this type of measurements. The basis of the groups, were the students studying the faculties dealing with motor technology or transport, like:

- Construction and Testing of Car Vehicles,
- Exploitation of Car Vehicles,
- Combustion Engines,
- Exploitation and Ratability in Transport,
- Exploitation and Mechatronics of Car Vehicles.

They have knowledge about the emission of toxic components of exhaust gases, as well as identification and classification of vehicles participating in the road traffic.
Each group was a team of 2 people, one of whom identified and classified the vehicles, and the other one wrote the results down in the specifically worked out cards. There are tables in the headline of the card, which are respectively:

- date and hour of the measurement,
- placement of the localization point,
- names of the members of measuring group,
- average speed of traffic in the time period of measurements.

4. Result of the research

4.1. Estimation of measurement error

Each measurement is burdened with a mistake. Estimation of exhaust emissions from motor vehicles involved in the actual traffic is a complex issue, subject to the formation of errors at each stage of the measurement and calculation. Part of the errors result from the introduced deliberately simplifying assumptions adopted for the project. These include for example:

- no account of certain groups of vehicles involved in traffic,
- combination of specific groups of vehicles,
- proposing emission factors for combined vehicle categories.

Other errors were accidental and resulted, for example:

- incorrect identification of vehicles as regards the category of emissions and engine type,
- mistakes resulting from errors in counting vehicles in the traffic stream,

In addition, it should be borne in mind that the project implements only random measurements of three selected days of the week and selected time intervals of 30 min at certain times of the day. The results obtained cannot be the basis for the development of a comprehensive communication model for the whole city, but merely a first step in the estimation of the amount of emissions that should be expected.

4.2. Presentation of measurement results

The results of measurements in the form of research material have the form filled measurement cards containing all the data needed to complete the project. Results from individual measurement cards were entered into the database according to the pattern received from the client.

The following are examples of research results, in graphical form, which were used to model of the emission transport in Cracow. The information relates only selected, for this article, types of streets and refer to measurements carried out on Thursday morning rush hour traffic.

![Figure 3. Number of cars per hour on highway (Thursday morning)](image-url)
Figure 4. Number of cars per hour on access road (Thursday morning)

Figure 5. Number of cars per hour on main street with accelerated motion (Thursday morning)

Figure 6. Number of cars per hour on principal street with tram track (Thursday morning)

Figure 7. Number of cars per hour on principal street with the tracks in the median strip (Thursday morning)

Figure 8. Number of cars per hour on a local street with tram track (Thursday morning)
5. Conclusions from the research

The study's conclusions apply to the analysis of the obtained results of the research on traffic flow of vehicles on specific sections of the road network, they constitute an important contribution to the development of a model of pollutant transport in Cracow agglomeration.

However, at this stage of research the following conclusions can be drawn:

1. this is the first research of this type, in which specialists able to identify vehicles that are the source of emissions took part,
2. the conducted research is particularly important for the agglomeration of Kraków due to the unique character of road traffic caused by a large, periodic influx of people (students, outsourcing companies, tourist traffic),
3. the unique geographical location with the lack of ventilation ducts and a strongly defined air flow direction
4. cars traffic flow is dependent, among others, on the type and direction of road, time of day and period of the week (weekday, weekend),
5. most of the vehicles in the streets of Cracow are passenger cars. In this group the most of cars are homologated at Euro 1-4 level,
6. in the passenger car group, there was no clear difference between the number of cars equipped with SI and CI engines,
7. the project was also aimed at checking in practice the chosen methodology for testing traffic streams of vehicles,
8. some of the emission models require two-way traffic to perform measurements separately for each direction of traffic, so the methodology used in the next phase of the project should take into account these requirements,
9. deeper analysis requires an estimation of the measurement errors resulting from both human errors and system prerequisites, eg. linking groups of vehicles and correct vehicle identification, for example. distinction cars with engines SI or CI,
10. in the presented stage of the project, the research goal was reached and knowledge and experience gained, which will be taken into account in the next stages envisaged.
Nomenclature

CI compression ignition  VAN delivery van and small bus
SI spark ignition      TRUCK truck and bus

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