„POLITEHNICA" UNIVERSITY of BUCHAREST

DOCTORAL SCHOOl within the
Faculty of Industrial Engineering and Robotics
Robots and Production Systems Department

DOCTORAL THESIS

DEVELOPMENT OF METHODS AND EQUIPMENT FOR INTERDISCIPLINARY APPLICATIONS OF MAINTENANCE

ABSTRACT

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Table of Contents

Note:

T – thesis
A - abstract

INTRODUCTION

Transport infrastructure is an extremely important branch as an integral part of a sustainable and balanced economic development of a society. Nowadays, when everything is done against time and any delay means the loss of resources, the mobility is vital.

Whether we are talking about road, railway, sea, airway infrastructure, all these contribute to the development of a nation. To the extent that the state manages to correctly define its priorities/strategies/policies in this field, we are able to talk about:

- balanced economic development;
- competitiveness among economic operators;
- European integration from an economic perspective;
- diminution of imbalances at the level of regions;
- development of some industries;
- easy access to resources etc.

The desire of citizens to have high quality infrastructure, especially high speed roads, is notorious. In this context the factor of infrastructure maintenance, as an essential element throughout the entire life of the road, must be taken into account. The doctoral thesis exposes some new technical concepts, such as the development of new equipment and technologies, starting from concepts used in the machine building industry, where coatings or welding operations of metallic materials, different in terms of chemical composition, are performed. This technology has been studied/analyzed for the sealing of the cracks that appear in the wear layer of the road surface in order to maintain the large surfaces in normal operation conditions, thus allowing the existence of modern, safe and sustainable roads infrastructure.

The equipment used in the field of road infrastructure, whether we are talking about:

- the one used in the actual construction stage;
- the one that has the role of ensuring an appropriate level of traffic service;
- the one that identifies degradations and enables the engineers to schedule the interventions, namely to make an efficient estimate of the maintenance,

is essential, that is why there is a constant need of development/innovation so as to streamline/ optimize as much as possible all these activities that lead together to the creation of a road infrastructure that meets the needs of the citizens.

When elaborating the doctoral thesis, two concepts were approached: the ecological concept and the economic one.

The ecological concept takes into consideration the conservation and the management of the natural resources, the use and recycling of the polluting materials, like the waste resulted from plastic bottles and/or tires of motor vehicles.

The economic concept aims at a new, innovative, safe, cheap but sustainable technology, approached after many experiences which led to the development of an inventive equipment, following the expansion and experimentation of devices and technologies from the field of mechanics, with transposition to the area of roads corrective maintenance. The result of the research work was the development of a new equipment of corrective maintenance and a technology different from the current one, for clogging the cracks in the wear layer of the road surface.

The main objective of the doctoral thesis is: the creation of a methodology for implementing the predictive and corrective maintenance of the systems with large surfaces, based on the digitalization and development of new technologies and equipment meant to apply a different concept from the current one, to promote clean (green) and non-polluting technologies.

The following objectives were considered and put into practice for the achievement of this scientific paper:

- Creation of digital maps for monitoring the systems with large surfaces;
- Creation of the methodology for implementing the predictive maintenance of the systems with large surfaces, applied to the roads, based on the digitalization of information;
- Development of a new technology for monitoring the roughness of the wear layer, using the thermal imaging camera;
- Development of a new concept and a digital equipment for determining the weight of a motor vehicle, used to monitor the stress of the national roads structure;
- Creation of a new, environmental-friendly method for clogging the cracks that appear in the wear layer of the roads;
- Making of an equipment with rotary tool for corrective maintenance and the calibration of this equipment;
- Study of the bitumen rod composition and of the concept used to make the rotary tool;
- Acquisition of the data regarding the sealing level by means of an experimental arrangement. Processing of the acquired data (drawing of diagrams);
- Interpretation of data and establishment of the efficiency of the cracks sealing method by means of a rotary tool made of bitumen.

The doctoral thesis includes six chapters, appendices and bibliography.

Chapter 1, entitled „*Current stage of the research on maintenance activities for the systems with complex surfaces”* looks over the present issues related to the maintenance of the complex surfaces, starting from the quality of the surfaces of an equipment sub-assembly and getting to the maintenance of road surfaces.

The current methods used in maintenance activity highlight the need to observe the quality of surfaces, regardless of the activity field (equipment, roads etc.). These methods demonstrate that the continuous (or at well-defined periods of time) gathering of relevant information, using complex monitoring systems, enables the entity that analyses the condition/quality of these ones, to take action efficiently, to define an annual/multiannual budget, maintaining the security, and to make a prediction of the management costs.

The problems related to the evaluation of surfaces condition are developed in Chapter 2 „*Assessment of the functional and condition parameters of the systems with large surfaces”.* It highlights the functional and condition parameters of the systems with large surfaces, with application to the roads network, and introduces the current methodologies for assessing the technical condition of the large surfaces (wear layer) of the modernized roads. This chapter shows the present techniques of assessment of roads condition and the periods of time when they must be performed, according to the established internal regulations.

Chapter 3, named „*The monitoring, basis of the preventive maintenance strategy”*, deals with the equipment for large surfaces monitoring (wear layer of roads), which allows the permanent collection of information necessary for the analysis of their condition and the decisions-making regarding the actions to take and the annual budget with the costs required to maintain a normal operation state. At the same time, this information makes possible the anticipation of defects long before they occur, by predicting their manifestation and development, as they are managed / monitored by means of digital maps.

„*Contributions regarding the development of methods and equipment for monitoring the large surfaces”* are presented in the chapter 4 of the thesis. The research shown in this chapter highlights the development of technologies specific to large surfaces (with application to road surface), the analysis and modelling of critical state parameters identified in the case of large areas, as well as the possibility to monitor and keep them under control. The analyzed disturbing factors (namely: weight of motor vehicles, existing roughness on the surface of the wear layer and the size of the cracks on large surfaces) bring into question the traffic safety and the normal transportation carried out regardless of the season. The research led to the development of innovative equipment and technical concepts, with positive impact on the environment, but maintaining the safety and quality of the roads.

Chapter 5 „*Contributions to the design of an equipment with rotary element for sealing the cracks in the activities of corrective maintenance”* introduces a new concept of corrective maintenance of the roads, which was the basis for the research and development of completely new equipment. The starting point of the research was the study of the operations / technology used in the machine building industry, respectively the friction welding with rotating electrode. The critical analysis of the current technologies and equipment used nationally and internationally for repairing the road cracks has led to the idea that they can be simplified by developing new technology and innovative equipment - simple, cheap but efficient.

The technology and equipment developed as a result of the research conducted during the doctoral study are new ones in the corrective maintenance of the roads, representing a **pioneering** approach in this field. **At the present moment there is no technology or equipment to seal the cracks in this way**.

Chapter 6 „*Final conclusions and personal contributions”* includes the final conclusions and the personal contributions to the field of maintenance of the large (wear and tear) surfaces, with application to the roads, and the future development perspectives. This chapter presents the research and the concepts developed in the doctoral thesis, the stages of the research study, the connections of the development of new equipment and technologies, environmentally-friendly, the so-called green technology, so much needed at the present moment.

The bibliography consists of 180 titles of technical and scientific papers, out of which 5 scientific articles already published or under publication, a laboratory guide for the maintenance of the technical systems and 25 links for web pages accessed from 2018 to 2021.

The Author

CHAPTER 1

CURRENT STAGE OF THE RESEARCH ON MAINTENANCE ACTIVITIES FOR SYSTEMS WITH COMPLEX SURFACES

1.1 Metrology of the bodies with large surfaces, the basis of decisions in the activity of maintenance

The detection and assessment of a defect is a process/activity used to determine with a certain probability the remaining life span for the technical system/roadway to fulfill the purpose for which it was designed, with performances within the range set by the designer. For this purpose, the maintenance activity (to keep the set performances of the technical system) has a defining role.

Maintenance is a combination of technical and organizational operations, necessary for the good operation/keeping in proper condition of the mechanical/technical systems, the large surfaces and – in the case of the roadways – of the wear layer.

This complex of operations is scientifically ordered and must be rigorously controlled. A team of specialists, motivated from all points of view, an adequate program of preventive maintenance and a proper procedure for the accidental interventions are needed for this activity. During the predictive maintenance, periodical checks and analyses are carried out regarding the behavior of the technical system / the characteristics of the large surfaces, in order to reduce, as much as possible, the accidental interventions. The sequence of technical operations in the activity of maintenance must be correctly arranged, taking into account the importance of the managed technical systems /roadways.

As in the case of the technical systems, the management of roads maintenance must include the monitoring of the large surfaces behavior in terms of compliance with the designed parameters. Thus their characteristics are maintained over time and the traffic is performed in safety conditions.

The maintenance plan may contain sheets (digital files) for observation/behavior of the equipment/surface (part of a maintenance software), analyzing and implementing the technical instructions and prescriptions.

At the same time, one keeps track of all activities performed or not yet-performed and of the future possible risks as well.

Findings and intervention reports are issued, on which occasion the characteristics of some related surfaces/components are also established.

The predictive maintenance activity takes into consideration the following matters:

i. the economic-technical criterion on the manner in which all the activities of maintenance are established, as well as the activities of correction/repair of the large surfaces (roads, associated constructions etc.);
ii. establishment of regulations for the organization, planning and monitoring of all maintenance and correction activities, as planned, in a timely manner (maintaining a normal and highly safe traffic which protects the environment);
iii. correction works of the large surfaces (corrective maintenance) that must be performed at certain intervals in order to maintain the proper operation, in safety conditions (assumed risk);

iv. monitoring the parameters that are key factors for the predictive, preventive and corrective maintenance such as: roughness, stress gradually caused by the weight of the vehicles which run on that surface, cracks and craters that occur and evolve over time.

Corrective maintenance operations include activities of repair and maintenance of the large surfaces of the roadway (wear layer), as follows:

a) activities and/or the so-called services supplying, created by the specialists in such way that we are able to talk about planning;

b) spontaneous interventions or those works required when an accident occurs.

In conclusion, we can say that the activity of maintenance and repair of large surfaces of roads, works of art and related elements, includes several preparatory services such as: preparation of all technical and economic documents; permanent concern for quality; proper management of roads network; transport monitoring.

1.5. Formulating the thesis objectives

Main objective: Development of methods and equipment for the implementation of the predictive and corrective maintenance based on the digitalization of information and on advanced techniques with applications to large surfaces.

Specific objectives:

- Analysis of the components with large surfaces and identification of the characteristics that require monitoring and which are decisive factors for predictive, preventive or corrective maintenance;
- Monitoring of large surfaces by creation of digital maps;
- Designing appropriate methods and equipment for interdisciplinary maintenance applications;
- Development of a new technology for monitoring the roughness of the wear layer using the thermal imaging camera;
- Development of a new concept and digital equipment, regarding the determination of the weight of a motor vehicle, independent of the will of the driver who uses the national roads;
- Creation of a new, ecological method for clogging the cracks that appear in the wear layer of the roadways;
- Creation of a mobile equipment for the corrective maintenance of the cracks as an application;
- Development of a mobile equipment with rotary tool for corrective maintenance;
- Study of the composition of the rod used as a rotary tool;
- Acquisition of data concerning the degree of sealing made by means of the mobile equipment;
- Processing of the acquired data (drawing of diagrams).

CHAPTER 2

ASSESSMENT OF THE FUNCTIONAL AND CONDITION PARAMETERS OF THE SYSTEMS WITH LARGE SURFACES

2.1. Assessment of the technical condition of the systems with large surfaces by creating digital maps - GIS

The measuring instruments are indispensable for the assessment of the functional and condition parameters of the equipment/systems with large surfaces. The commissioning of a complex system (equipment, railways etc.) can be made through the process of measuring the functional parameters in the case of equipment /systems with large surfaces.

In order to obtain a high productivity corresponding to the manufacturing of equipment/systems with large surfaces, one must ensure the control that is performed in all situations. It must be economical at the same time, as a result of the inclusion of the share into the controlled product/system.

Real-time analysis and information about the integrity and condition of the systems with large surfaces is a major goal for builders, users and maintenance team too.

The monitoring of the systems with large surfaces offers a number of advantages, like:

- efficient use/operation of the systems with large surfaces, through continuous monitoring;
- shortening of the system downtime, avoidance of the accidents by reducing the risks of accidental defect.

At the same time, the monitoring of the systems with large surfaces and the long-term automated maintenance reduce the subjectivity of the human factor and consequently the human errors, maximizing the safety and reliability of the systems with large surfaces.

The great advantage of using GIS systems is the possibility of converting a stand-alone (non-spatial) table into a set of spatial data. In the case of an institution in the field of transports, there are two options for achieving this transformation (fig. 2.1):

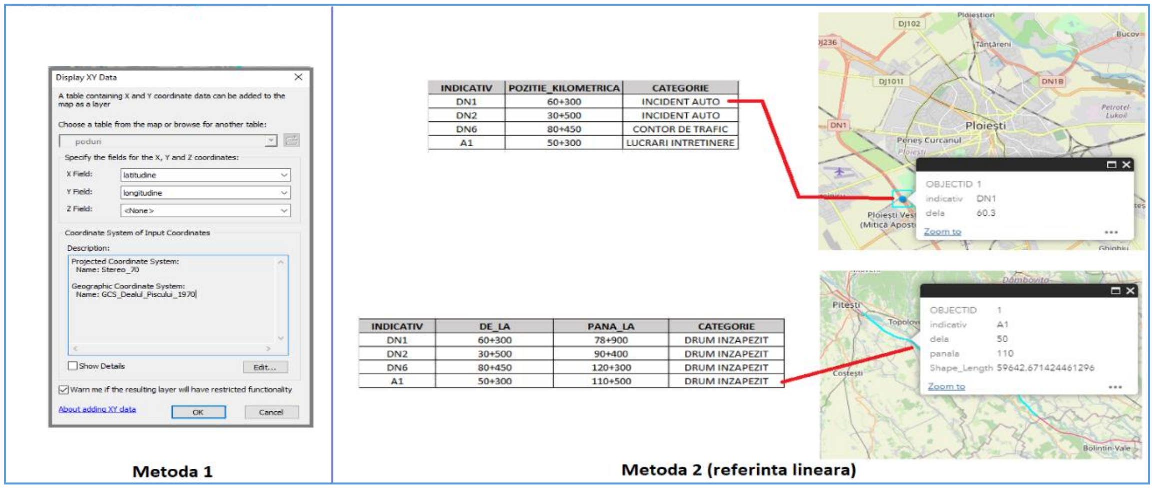


Figure 2.1. – Methods for automatically obtaining the spatial data based on non-spatial tables

1. the columns in which the geographical coordinates are stored (x, y);
2. a kilometric position can be placed on the map by means of roads network with linear reference (obtained on the basis of the kilometer posts).

At the beginning of the 2000s, the project on the Digitalization of Romania was started (e.g.: road networks, hydrographic networks, administrative boundaries, land use etc.). This fact is an advantage at the present moment, because:

a. the accession of Romania to the European Union entailed the duty of our country (like the other member states) to contribute to the achievement of the requested spatial data. The Ministry of Transport appointed CNAIR/CESTRIN to carry out the items I.7. – Road transport networks and III.11 – Restriction zones (noise maps);
b. using the spatial data, it is possible to keep track of the entire roads network (in real time) with the associated elements (condition, traffic counters etc.). The roads network administrator decides on the level of details, on the basis of analyses regarding the technical and economic ratio between the necessary investment – in terms of costs - and the level of details considered to be sufficient);
c. using the WebGIS type services, spatial data can be shared with the European institutions, and the specialized companies can use these digitization data to obtain applications available to the general public (for example: Navteq, GoogleMaps, Waze, Garmin).

By digitalizing the world where we live, we can use the spatial data to perform spatial analyses (e.g.: how many gas stations/parking lots exist within a radius of 10 km related to the spot where I am located). Following such an analysis, a decision can be made (fig. 2.2):

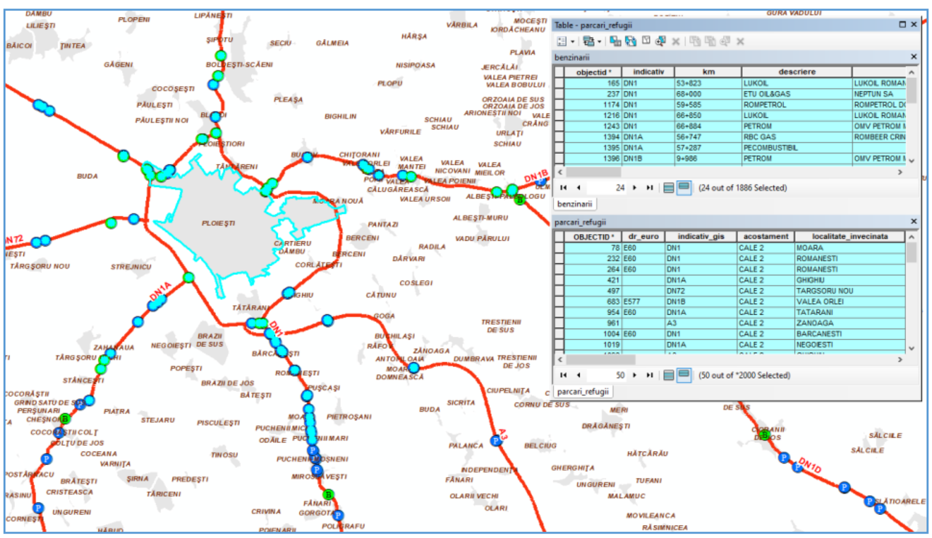


Figure 2.2. – Example of spatial analysis – Selection based on location
Source: CESTRIN GIS database)

Within an institution, GIS can be the tool that highlights the activity of several specialized offices. By querying the GIS database, we can quickly answer certain questions, because the reports, statistics, thematic maps and spatial analyses can be obtained automatically.

As they have a coordinate system, the GIS databases are able to calculate surfaces, distances and volumes, taking into account the Curvature of the Earth and the local landforms differences.

The purpose of GIS databases is to represent in the most harmonious way possible the world in which we live (e.g.: roads, railways, kilometer posts, rivers, trees, buildings). Only three entities are needed for this: point, line or polygon.

2.3. Conclusions

In order to have a high efficiency when monitoring the risk factors in the case of the systems with large surfaces, it is also recommended to use the GIS systems for analysis and synthesis, in addition to the classic monitoring technologies.

Transforming tabular data into GIS databases is useful in maintaining the functionality of the large surfaces. Also, the GIS database can be efficiently used in the continuous analysis of the large surfaces damages (roughness, cracks etc.), but also in the management of the disasters.

GIS is an instrument that can be used for decision making (for example: predictive maintenance).

At the present moment, the road traffic in Romania is in metering progress, by means a multitude of sensors located on the top or even inside the roadway. Thus, the installation of sensors in the drainage system will make possible that the data received and associated with information about the duration and intensity of the zonal precipitation are used efficiently in the anticipative maintenance. Subsequently, decisions can be made to prevent the flooding of the road infrastructure. Moreover, these data can be used in dedicated computer applications for modeling the operational decision, with beneficial effects on the performance of the road infrastructure.

CHAPTER 3

THE MONITORING, BASIS OF THE PREVENTIVE MAINTENANCE STRATEGY

3.1 . Structure of the monitoring system

As a result of the research carried out in the zones where large surface degradations occur, it turned out that there are major inconveniences in the analyses that appear after the visual inspections. This fact led to extensive programs of research development, dedicated to the modern concepts of optimal integration of the interventions for improving the maintenance of surfaces [108]. This research arises following up the understanding of the need to take over highly important information regarding the large surfaces, from the entire road network.

A transport network is formed of the following elements:

a) zones (zoning system of the national transport network, traffic generating zones);
b) arcs (in the form of links, which are associated with roads, streets etc.);
c) nodes (usually associated with road intersections).

In the developed model, the nodes delimit the ends of the arcs//links. The parameters of the nodes are used to define the type of traffic guidance in an intersection or its organization, such as: traffic lights intersections, roundabouts etc. [109].

The transport network graph was developed from the geo-spatial database (OSM) downloaded via OpenStreetMap.org. The OSM type database includes the following sets of information (table 3.1):

Table 3.1. Primary information from the OSM database

Parameter	Accuracy	Remarks
Name	Good	
Type of road	Low	It does not correlate with the hierarchy of roads network of our country
Length	Very good	
Hourly capacity	Low	It does not comply with standards and norms
Number of lanes	Low	
Permitted speed	Low	No distinction is made between urban and extra-urban environment
Public transport stations	Low	Insufficient information
Vehicles allowed	Low	Insufficient information; only cars and trucks are allowed
Other information		Not relevant for the model

3.2 Hierarchy of the monitored information

Given the lack of consistent and realistic information, considerable effort has been made to abstract the network (reducing the number of arcs and nodes) and to populate it with information needed to develop the model. Thus, besides the corrections applied to the previous parameters (name, type of road, capacity, number of lanes, permitted speed), the road network was populated with the following parameters:

d) Type of landform (3 categories - mountain, hill, plain);
e) Technical condition of the road (5 categories – very good (5), good (4), average (3), bad (2), very bad (1);
f) classes of vehicles allowed (4 classes – Cars; LGV = Light Goods Vehicles for goods transportation < 3.5 tons; HGV= Heavy Goods Vehicles for goods transportation; it includes 2-axle trucks, 3-4 axle trucks and articulated trucks; BUS – assigned as a fixed part of MZA / AADT);
g) urban or extra-urban sector;
h) post census or post survey coding O-D;
i) toll used on the bridge for each of the 4 classes stated above;
j) toll for crossing the Danube by ferry-boat for each of the 4 classes mentioned above;
k) proposed connections (highways, express roads etc.) and the estimated horizon for putting into service.

The national modeled network (fig. 3.1) contains a number of approximately 12,500 arcs and 9, 900 nodes; it is sufficiently detailed to include all highways, national roads and more than 70% of the existing county roads.

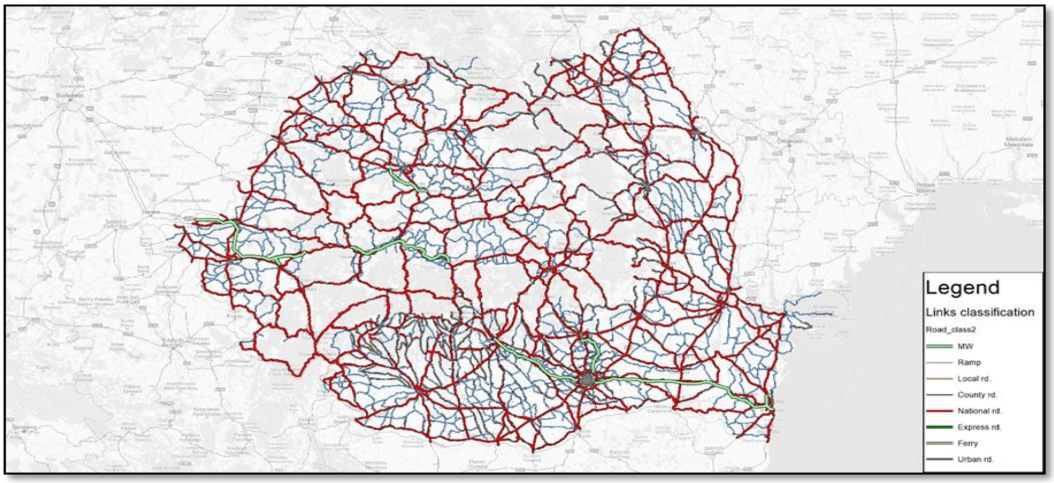


Figure 3.1. Road network (CESTRIN-2017)

Some of the attributes of the internal network are listed below:

- name;
- type of road;
- speed;
- length;
- traffic capacity;
- number of lanes;
- technical condition;
- geographic relief;
- coding after census/surveys OD;
- sinuosity;
- bridge/ ferry-boat tolls.

3.6. Conclusions

Roads monitoring uses modern technologies for real-time collection and transmission of information, both for timely interventions in the roads infrastructure and for keeping informed the users of goods and people transportation.

Currently, the intensive use of the automation and digitalization can contribute to the increase of the efficiency of maintaining the optimal operation of the roads for a long time. Thus the roads safety is improved, the negative impact of the exhaust emissions on the environment is reduced, while traffic blockages are kept under control.

This chapter presents the main ideas about roads surfaces monitoring, along with some data regarding the permanent connection between monitoring and the moment when the maintenance and repair works are included in the sector budget (from the earliest stages of the wear). At the same time, there were examined some of the new concepts concerning the early analysis of surface wear with the help of the prediction and monitoring system.

By correlating and digitizing all data and by integrating them into a transport model, a strategic transport model can be generated at national road network level, through a prioritization of maintenance works based on an integrated and transparent management.

CHAPTER 4

CONTRIBUTIONS REGARDING THE DEVELOPMENT OF METHODS AND EQUIPMENT FOR MONITORING THE LARGE SURFACES

4.1. Roughness – deciding factor of maintenance activity

In the machinery manufacturing industry, the surfaces of the metallic materials, even if they are apparently perfect, have geometric shape deviations and irregularities, which are determined as a result of the technological processes [54]. The shape of the surface of a semi-finished product can be characterized and compared to the ideal shape, by the following sizes:

- maximum height of the irregularities;
- the distance between 2 successive irregularities (pitch).

Depending on the size of the irregularities, the geometric deviations are divided as follows:

- first order deviations (macroscopic defects or shape deviations);
- second order deviations (corrugations);
- third order deviations (microscopic defects);
- fourth order deviations (tears**,** tool marks and gaps) [1].

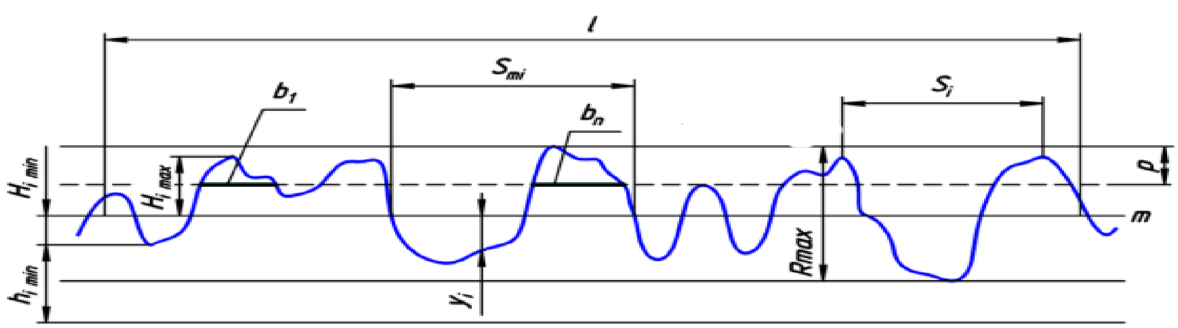


Figure 4.1.

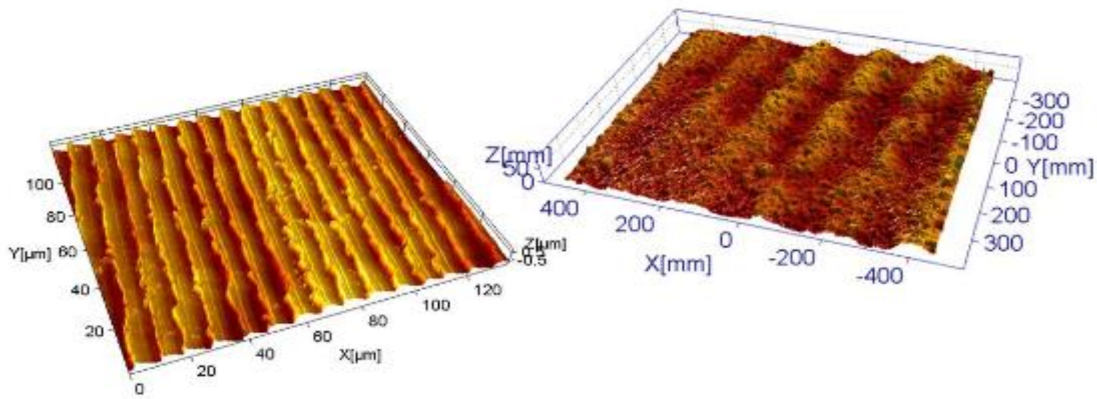


Figure 4.2.

The height variations of a physical surface can be measured by means of mechanical feelers or by optical methods in one direction (fig. 4.1) or three-dimensionally by scanning (fig. 4.2) [50]

4.2.2. Creation of a system for the assessment of surface micro-asperities on the basis of virtual instrumentation

At the present moment, when informatics entered all activity fields, the measurement process underwent important changes, not so much metrological but especially methodological ones. The main change consists of the transition from classic instrumentation, mainly analog, to the predominantly numerical instrumentation, in which the computer has an important role.

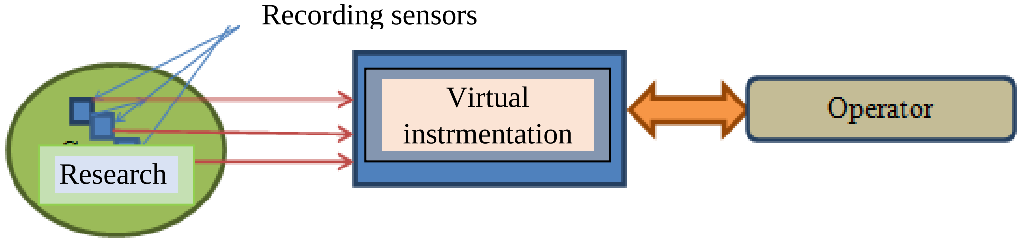


Figure 4.5. Operation principle of the measuring equipment

The virtual instrumentation for measurement and control used in the research is intended both for the processing of the information collected by measurement and for the elaboration of the commands for the execution components that actuate the studied process (fig. 4.6).

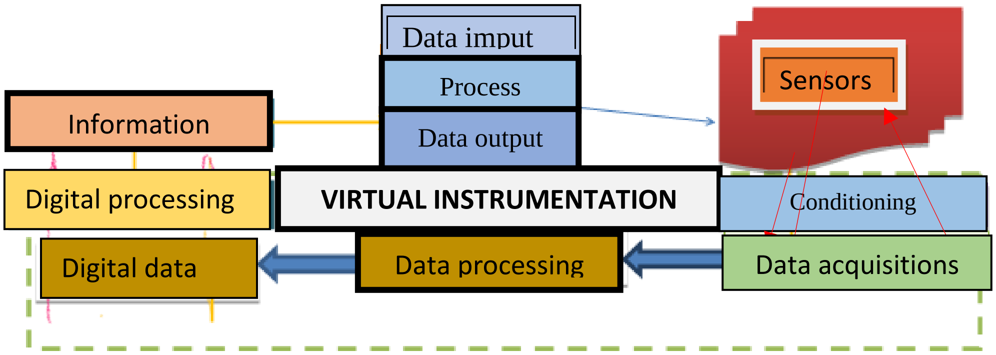


Figure 4.6. Virtual instrument for analysis

The infrared measuring instrument with linear scanning in several points (fig. 4.7) can also determine and shape graphical profiles of the temperature. This system can be associated/switched to a data acquisition system, which can associate the temperature of the microasperities on the roadway surface, leading to the measurement of its roughness (equivalence of the temperature points to the roughness value) in real time.

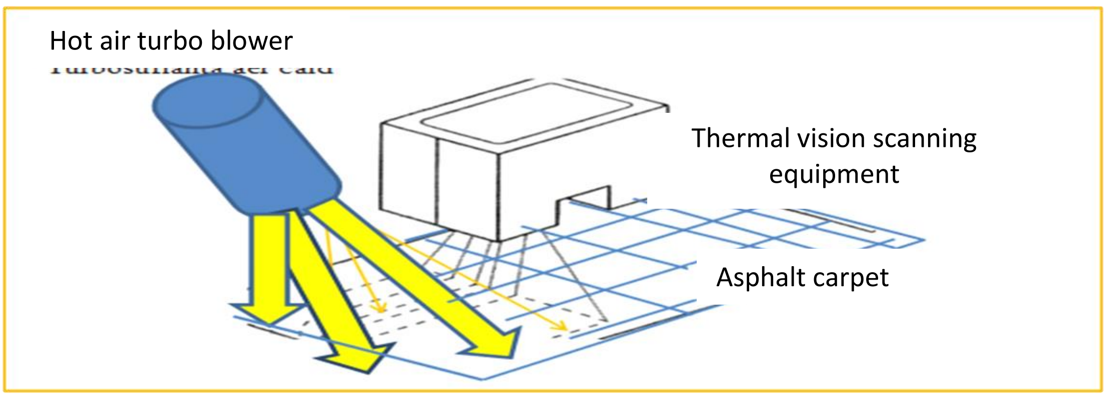


Figure 4.7. Infrared measuring instrument

If we watch the images recorded by scanning with thermal vision camera and we analyze the contrast/ contrast ratio, which is represented by the ratio between the brightest zones and the darkest ones that make up the images captured at the two moments (initially / after a period of use), we notice that there are different color tones at the acceptance of the work and close tones after a period of use of the asphalt carpet. The visualization of the number of color tones that can be identified with the naked eye or by means of the tone scales must not exceed 8 at the most.

Reduced color tones (in number of 3) are identified on almost the entire scanned surface; thus we can conclude that we deal with a low roughness as the temperature of the peaks of the micro-irregularities is approximately equal to the temperature of the air sent by the turbo blower, points 1,2,3,4 (fig. 4.10).

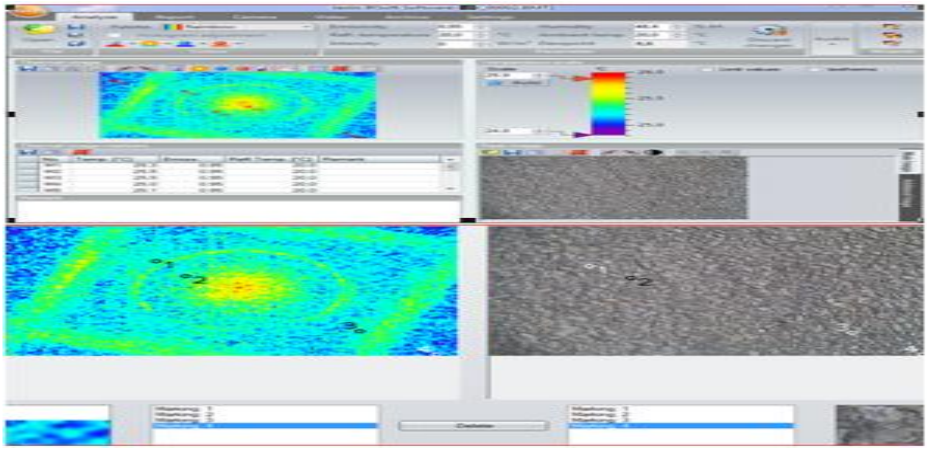


Figure 4.9. Initial visualization of asphalt surface T_0

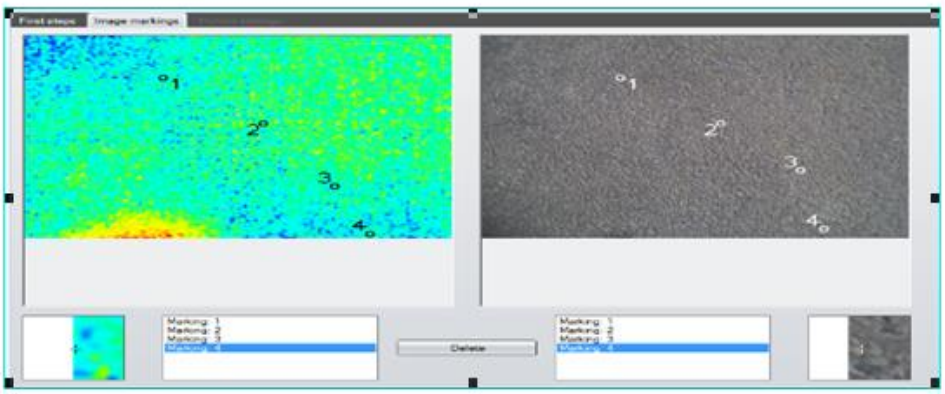


Figure 4.10. Color spectrum of asphalt surface at $T_{1\ (120\ \text{days})}$

From the two figures 4.9 and 4.10, we notice that the roughness of the wear layer decreases over time, in proportion to the deterioration of the poor quality aggregate particles.

4.3. Design of a weight monitoring intelligent system

The minimization of road risks is currently a large field for research and is constantly addressed by the relevant authorities. The road authority is currently facing a major problem that influences the roads safety, namely the permanent efforts required to maintain the roads infrastructure in optimal condition even when motor vehicles are detected in traffic with loads over the declared value of transited weight. The analysis and keeping under control of the degradations occurred in asphalt surface because of exceeding the maximum value of the declared weight of a motor vehicle must be recorded to highlight the influence upon the wear layer as time goes on.

In the case of motor vehicles, the running system ensures the contact with the roadway, takes over the forces and actuates the means of transport, generating the motion. The connection between the motion taken over from the motor and transmitted to the running system is shown in figure 4.13.

The torque developed by the engine of a motor vehicle is maintained and transferred by means of the longitudinal mechanical transmission to the drive wheels (torque at the wheel), as shown in figure 4.14.

$$M_R = M \cdot i_{tr} \cdot \eta_{tr} \tag{4.5}$$

where:

- M_R, moment transmitted to wheel
- M, actual moment
- i_{tr}, transmission ratio of the motor vehicle transmission
- η_{tr}, transmission efficiency.

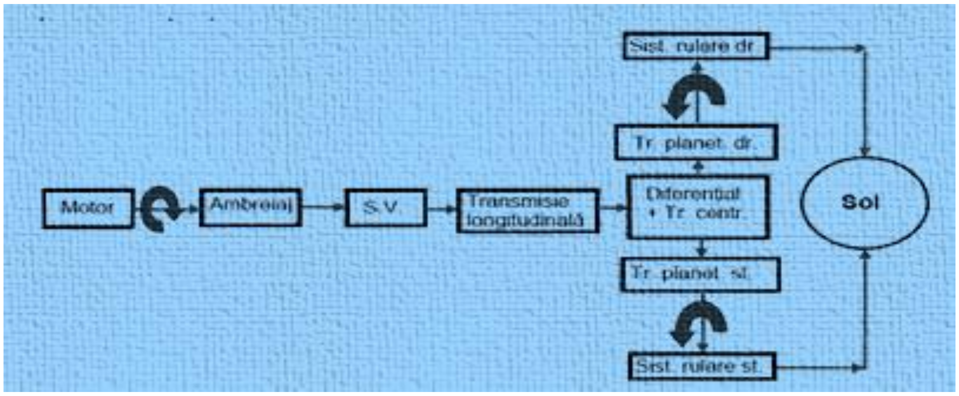


Figure 4.13. Transfer of motion from motor to the running system

The forces that act on the drive wheels (non-deformable) are taken into consideration and the roadway (the road) is rigid (fig. 4.14).

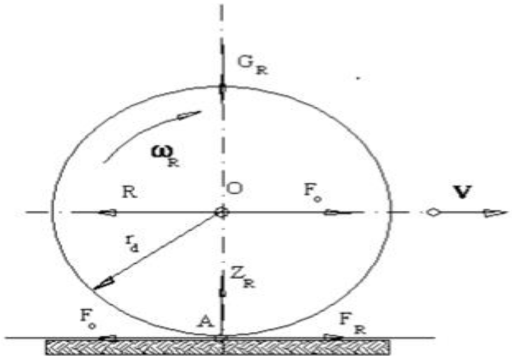


Figure 4.14. Forces that act on the drive wheel

The moment M_R transmitted to the wheel by the torque (F_o , F_o) has the arm equal to the radius of the drive wheel (r_d). The reaction force F_R, respectively the force at the wheel [132], are produced at the contact spot between the roadway and the wheel (point A).

In the case of the vehicles with motor combustion engine, the important elements for the engine control are the following ones: crankshaft rotation speed and vehicle speed.

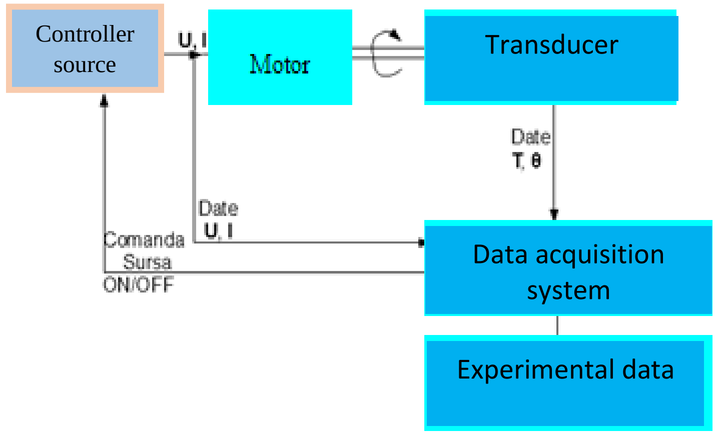


Figure 4.17. Experimental measuring system

The engine rotation, in most vehicles, falls within the range 900....8000 rpm. Thus, the necessary measurement resolution is about 10 rpm in order to obtain an accuracy of 0.2 % approximately. In this context, the typical speed range of the motor vehicle is between 0 and 100 km/h. It should be mentioned that the motor vehicle speed can be automatically reduced in safety conditions, on certain segments of the road, where overtaking is prohibited.

So, the crankshaft torque can be determined by means of magnetic transducers. Ring magnets with 4 - 20 poles are usually used, depending on the resolution.

4.4. Monitoring the large surfaces by means of digital maps

The *Hawkeye 2000 System* is currently used to create digital maps. This system has two distinct parts, namely:

a) a data acquisition package, consisting of a collection of modular hardware devices and software modules assembled on the on-road research vehicle;

b) a Processing Toolkit and Data Viewer that makes it easy to view, manage, interact and report the numerous data collected by the on-road research vehicle. One must keep in mind that the processing package is also used for the processing of the data from other ARRB systems and is not dedicated to Hawkeye 2000 System only.

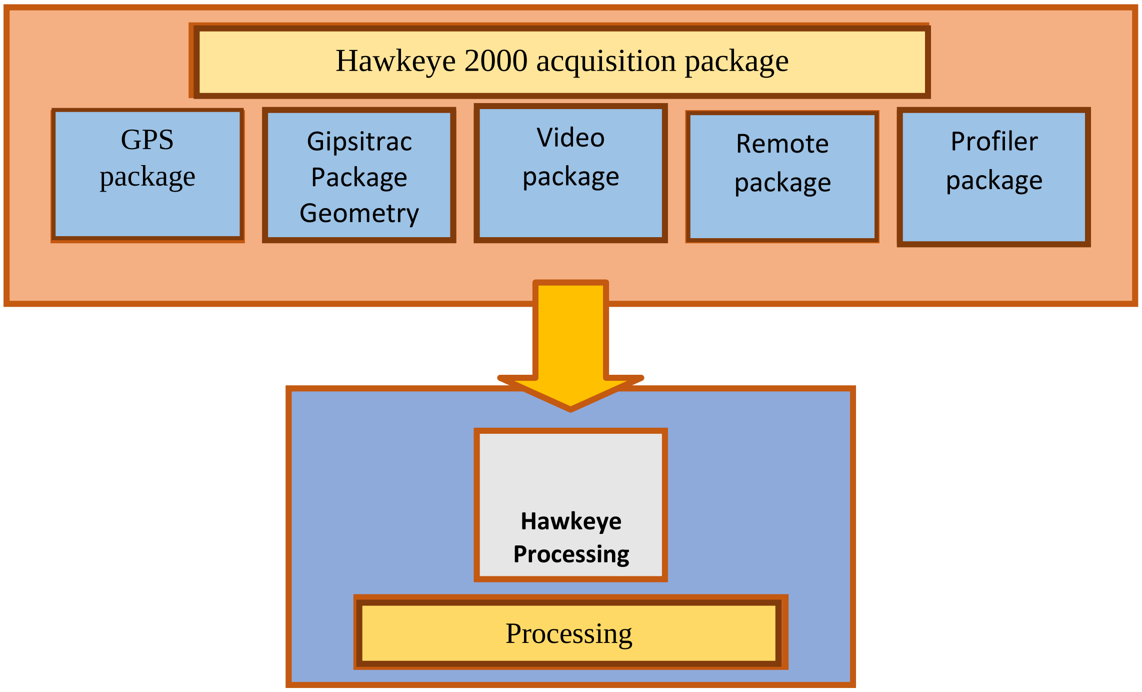


Figure 4.19. Data acquisition system

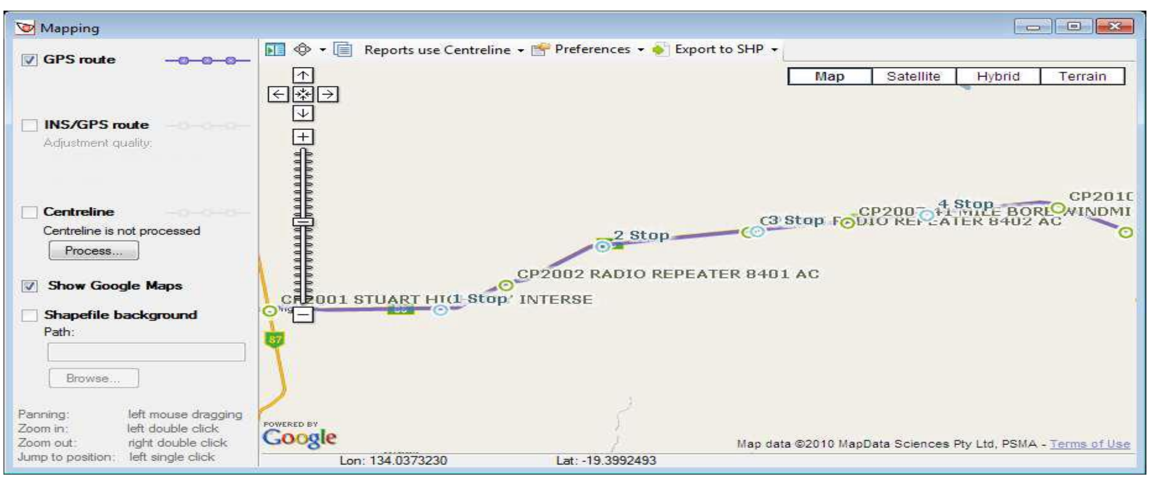


Figure 4.22. Representation of the route in GPS coordinates in the Processing software

4.5. Conclusions

The transition from measuring the roughness of small surfaces (equipment components) to measuring the roughness of large surfaces (roadways) is a necessity in order to assess the product quality (in the case of parts) or a requirement for transport safety. The large surfaces quality provides the information necessary for the monitoring and digitalization of the road map, making possible an anticipation of the degradations but also an anticipated zonal budgeting. Complex monitoring systems are currently used. The systems studied and developed following the research works are simple but ensure sufficient accuracy, in conformity with the national regulations.

So, the GIS system is one of the new information technologies that were able to deeply transform the manner in which the road workers perform the anticipative maintenance operations in order to eliminate the road risks.

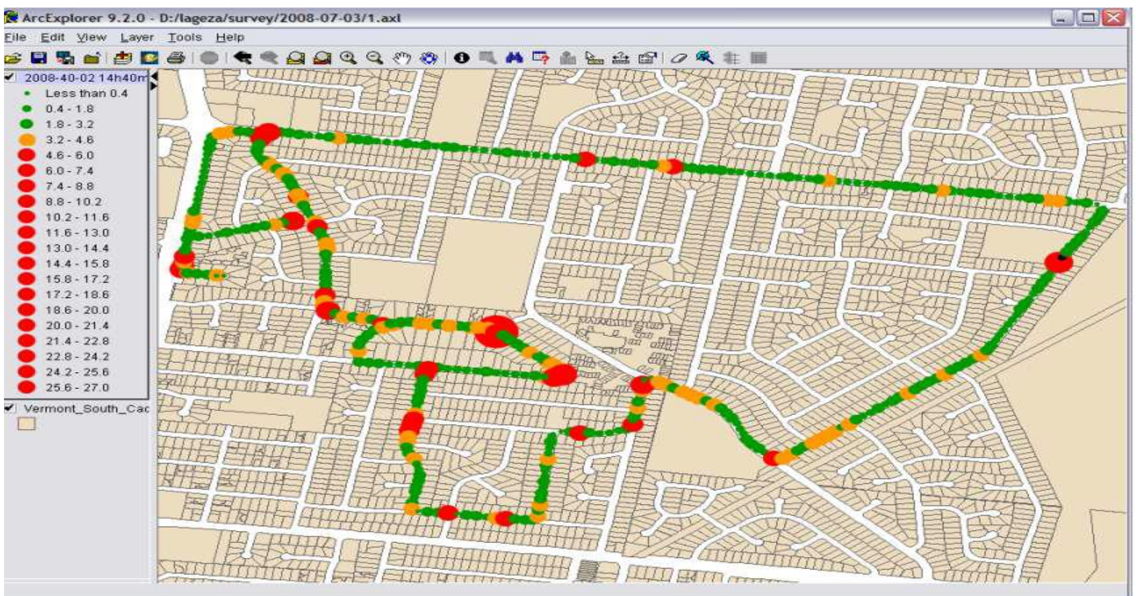


Figure 4.29. Roughness displayed in GIS

The GIS system used at the present moment is very efficient for the decision-making in roadways maintenance field. The IT process by which data are retained and analyzed within the GIS system must highlight how the information will be used for research or for an operation based on the need for a decision.

The two research works connect and improve the data entered into the digital map, leading to the appropriate decisions. The system can be programmed so that when it reaches the upper limits of some entered parameters, it communicates with the maintenance operator who came to the field for information and decision.

CHAPTER 5

CONTRIBUTIONS TO THE DESIGN OF AN EQUIPMENT WITH ROTARY ELEMENT FOR SEALING THE CRACKS IN THE ACTIVITIES OF CORRECTIVE MAINTENANCE

5.1. Corrective maintenance of the roads

Two technological processes are frequently used in industry, namely: friction deposition with a rotating rod made of consumable material on a semi-finished product (friction surfacing) and welding of two semi-finished products by friction with an active rotary element (friction stir welding)[50].

These methods are essentially based on the same principle, the rotation of a rod/electrode and the generation by friction of the temperature necessary for the material deposition/welding of two materials. In the first case (deposition) it is noticed that the concentrated thermal energy developed in the contact area between the electrode/rotary rod and the semi-finished product leads to the generation of a layer of plasticized material which adheres to the surface of the semi-finished product if there is an advance movement made in a perpendicular direction. As it is consumed, the electrode bar / consumable rod is advanced axially to perform the deposition process [14]. In the second case (welding), the joining between the two semi-finished products is based on the heat achieved by friction and plastic deformation generated by a tool (active rotary element), which carries out a rotational movement around its axis, penetrates transversely into the joining parts, making a translational movement in the joining direction (fig. 5.1). Thus, the plasticized material is transferred behind the rotary element, making the welded joint [3].

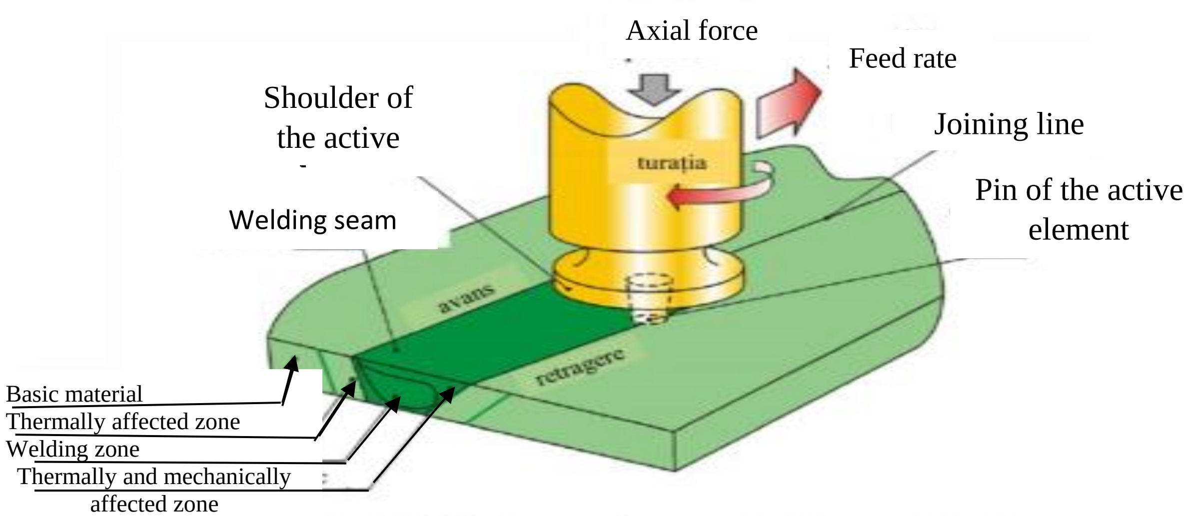


Figure 5.1. Principle of the welding process with rotating electrode

5.2. Design of an equipment for cracks sealing

The selection of a method for sealing the cracks generally depends on four variables:

- the crack characteristics that take into account the type of crack (active/inactive);
- the need to achieve or not a joint along the crack;
- the unevenness induced on the roadway after clogging;
- the amount of material required for sealing, characterized by the size of crack opening.

The clogging methods are grouped into four categories:

- 1. simple clogging without mechanical interventions at the crack;
- 2. clogging with mechanical realization of a joint along the crack;
- 3. clogging with provision of excess material on the road surface for a better protection of the crack sealing;
- 4. Combination of the methods 2 and 3.

Simple clogging without mechanical interventions at the crack

The material is simply forced into the existing crack and, once filled, the crack is leveled so as not to induce bumps in the road surface (fig. 5.7). Generally, this methodology is used before applying a surface treatment.

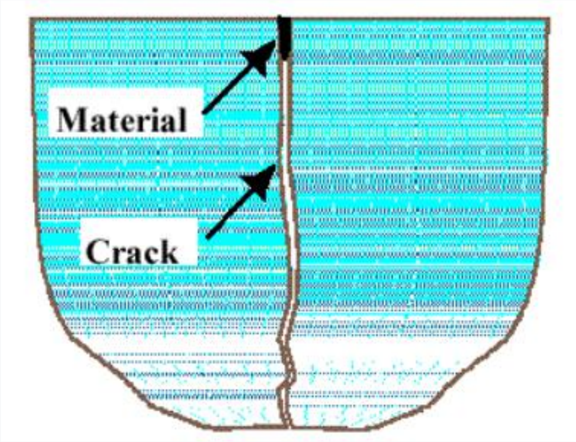


Figure 5.7. Simple clogging

Clogging with mechanical realization of a joint along the crack

The specific character of this method is the mechanical treatment of the cracks by making a joint. The crack is cut and guided to form a joint that will be filled with sealing material (fig. 5.8). **Johnson et al. (2000)** state that the directing of the transverse cracks improved the sealing performance while the longitudinal cracks directing was not necessary.

Clogging with provision of excess material on the road surface for a better protection of the crack sealing

The material is simply forced to enter into an existing crack. If the excess material is formed into the shape of a strip, using a scraper, this method is also called Band – Aid.

The technology used for clogging the fissures/cracks that have an opening larger than 8 mm is shown below:

- specific tools are used, slightly rudimentary (chisel, pickaxe, hammer etc.), making a slit along the crack;
- in order to achieve an efficient sealing, the fissure/crack is cleaned with specific tools (brush, compressor etc.);
- a bituminous primer with emulsion is applied after cleaning;
- the asphalt mixture is applied in the cleaned area, followed by compaction.

Figure 5.11. Cleaning of cracks

Figure 5.12. Clogging of cracks

Nowadays, in Romania, CNAIR uses the cracksealing machine HYDROG ZSK500 with 500 liters vertical tank. The equipment is used for joints sealing, cracks repair and roadside elements sealing, figure 5.13.

Figure 5.13. HYDROG ZSK500 equipment (CNAIR) [89]

5.3. Experimental arrangement

The maintenance works at the level of fissures and cracks were based on the comparative analysis between the approaches, starting from the optimal moment of the year and the cost – benefit ratio, versus the national approach.

5.3.1. Description of the sealing method with rotary element

The proposed method is based on the rotation of a consumable bitumen rod (with rubber powder and plastic granules), pressed against the surface to be repaired, in order to deposit a layer of material into the crack, making the sealing (stopping the water penetration). One analyzes the concentrated thermal energy, developed in the contact zone, that leads to the generation of a layer of material covering the crack, under the conditions of the existence of an advance movement made perpendicularly to the axis of the consumable material bar.

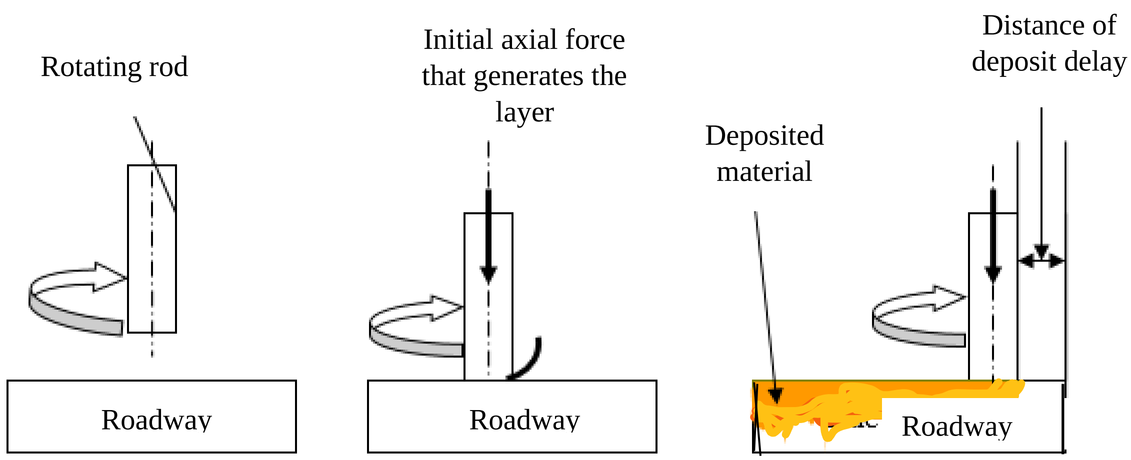


Figure 5.14. Friction sealing

The rotating rod is moved axially as it is consumed, to achieve the deposition and sealing process (fig. 5.14). Following the measurements, the deposited layer has a width of about 0.8 of the diameter of the bitumen rod. As a result of reaching a controlled temperature at the impact surface, the material turns into viscous state and penetrates the crack to a depth that depends on the temperature of the substrate [4].

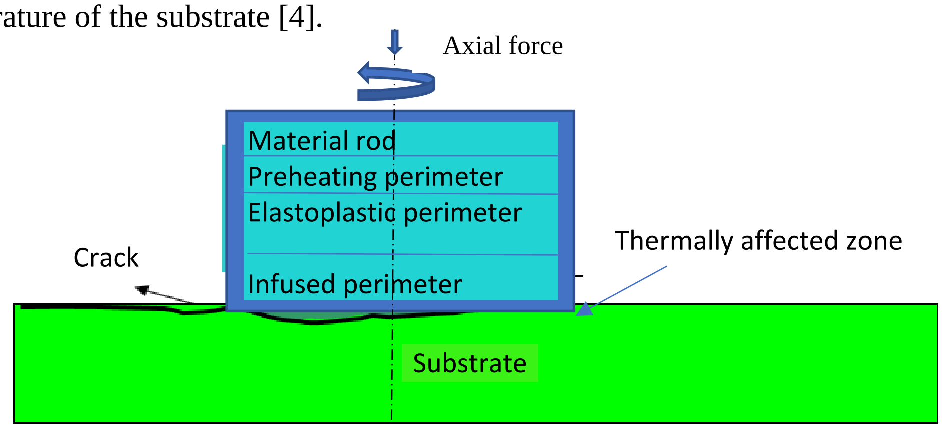


Figure 5.15. Parameters of friction crack sealing

The friction mechanical work is transformed into heat that is transmitted, on the one hand, to the rotary element and determines the passage of a quantity of material from solid state to viscous state (80^{0}C up to 120 ^{0}C at the contact surface), and, on the other hand, is transmitted to the roadway. The higher the temperature of the substrate than 5°C, the bigger the penetration depth than 7mm. In case of temperatures of the wear layer higher than 20°C, the bitumen penetrates up to 15 mm. At temperatures of the wear layer above 40°C , the feed rate of the bitumen rod must be increased, so that the contact time decreases in order to obtain a constant depth of penetration of the bitumen into the crack.

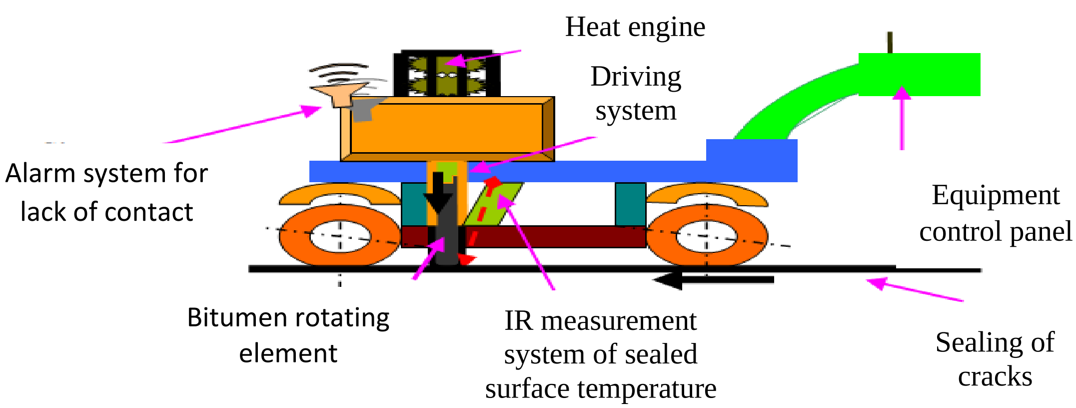


Figure 5.17. Cracks sealing equipment with rotating bitumen rod

The temperature measurement system, correlated with the axial advance of the rotating element and with the rotational speed, make possible the efficient sealing of the cracks by depositing a sufficient amount of material to penetrate the crack and form a layer higher by 3

- 4 mm than the roadway, fig. 5.18. The excess material can be easily removed using a device independent of the equipment.

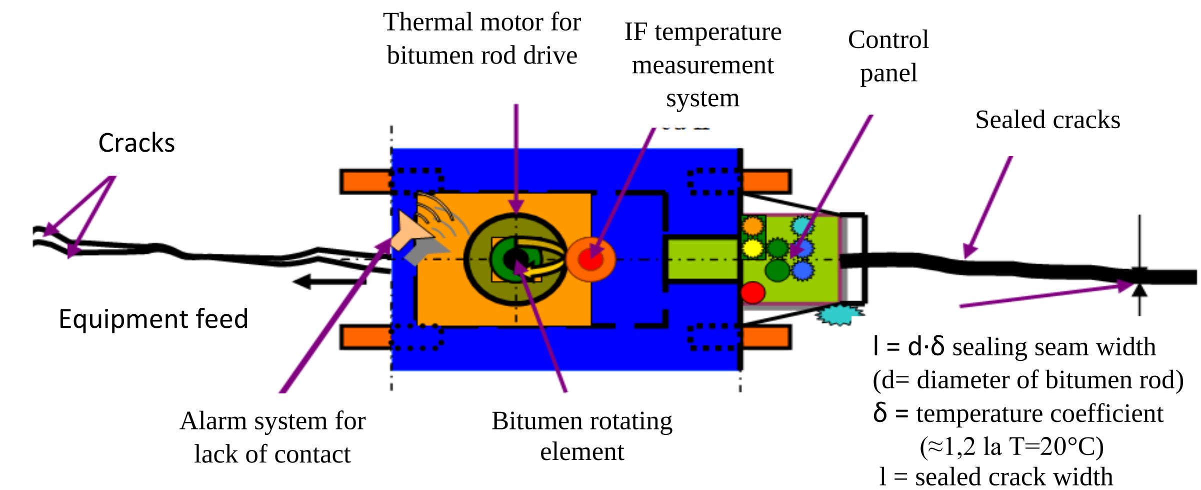
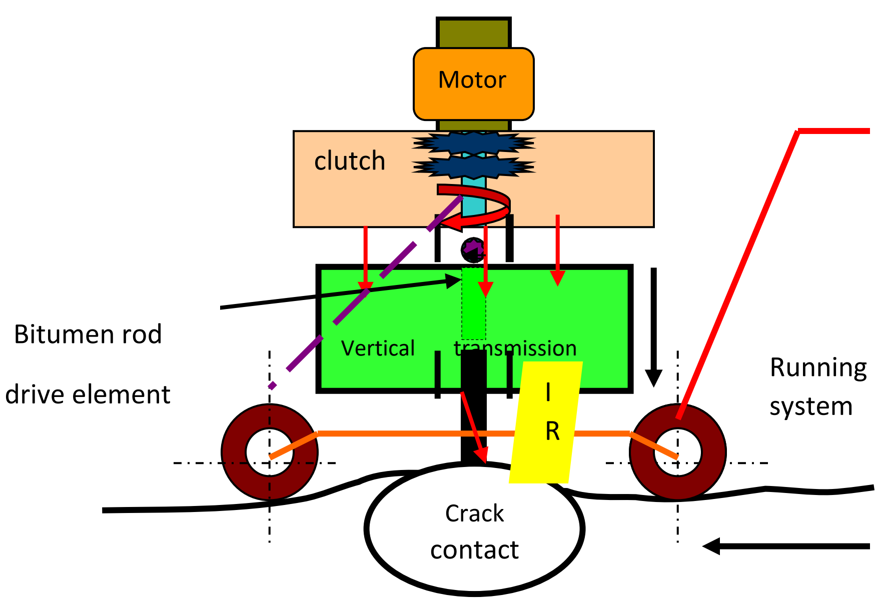


Figure 5.18. Cracks sealing equipment (top view)

The kinematic diagram of the experimental equipment proposed for performing the crack sealing operations in the wear layer of the roadway is shown in fig. 5.19.

The kinematic diagram is formed of the kinematic chain, motor, clutch, motion transmission shaft, drive system and bitumen rod. The equipment includes a vertical feed system that presses the bitumen rod against the crack surface; the melting of this rod makes the sealing (deposition of material).



5.19. Kinematic diagram of the equipment

The feed rate is correlated with the IR temperature sensor. The travel along the crack can be made manually or automatically by coupling the drive mechanism to the wheel of the equipment.

5.4.3. Main process functions for sealing in dry environment

If the input technological parameters or the independent variables are denoted by A_i, the process parameters or the semi-dependent variables are denoted by B_j and the output factors are denoted by C_k , the influence of the independent and semi-dependent variables upon the dependent variables has the general form:

$$Ck = fi\,(Ai, B\boldsymbol{j}) \tag{5.5}$$

$$C_k = Raf = f\,(Rai, HRC, Pl, Lc). \tag{5.6}$$

With the help of these parameters it is possible to establish mathematically the sealing of cracks by depositing the bitumen resulted from the friction process on the roadway.

The steps of this program, called „Experimental sealing program", symbol„Pexp. Sealing", includes 90 experiments, structured in 4 complete levels, each one with 10 tests (P1......P4) (fig. 5.23, 5.24, 5.25. 5.26).

Figure 5.23. Sealed crack

Figure 5.24. Sealing seam

Figure 5.26. Sealing tool

Figure 5.27. Roughness after cracks sealing

5.5.5.2. Influence of some factors on the deposited material volume, Vd

Graphs of variation of the deposited material volume, *Vd* , depending on the three parameters:

$$V_d = f(D_{er}, N_{er}, V_a)\ . \qquad (5.16)$$

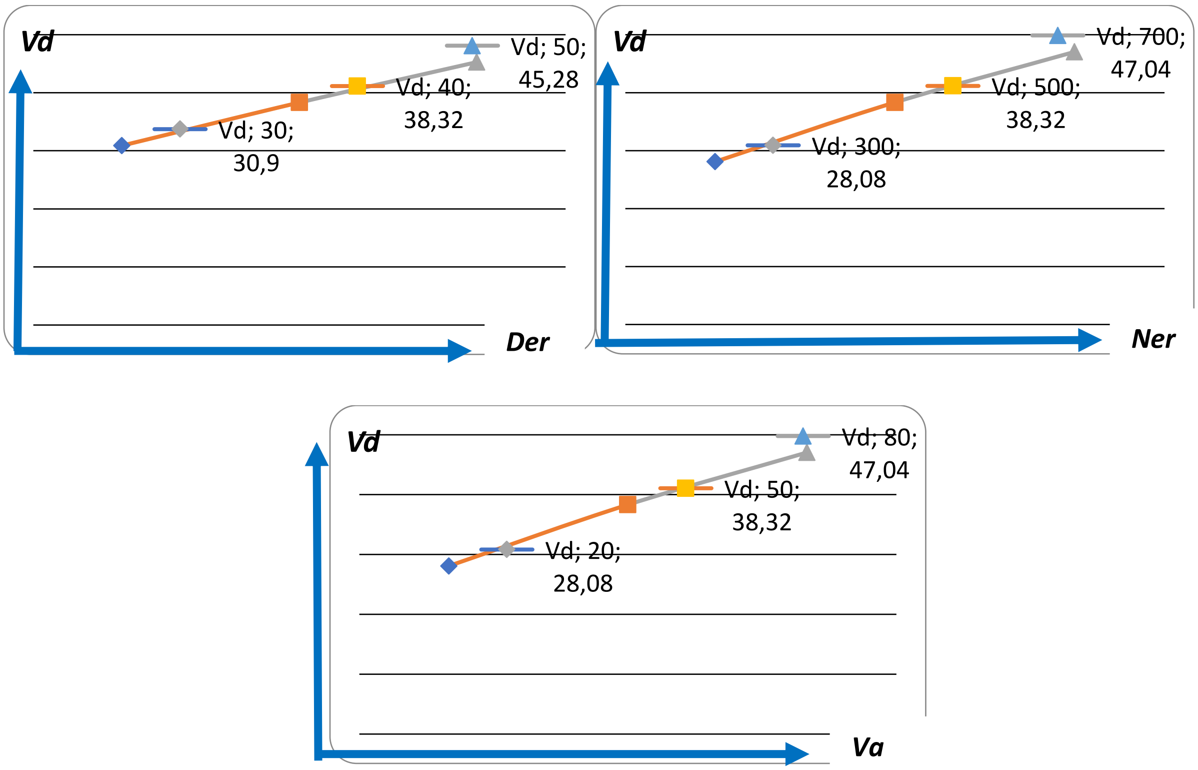


Figure 5.30. Variation graphs of the material volume depending on *Dr*, *N* and *Va*

The graphs are presented in figure 5.30. The study of these graphs shows us that the volume of deposited material, *Vd* , has an increasing tendency on the variation intervals of *Der, Ner* and *Va*.

5.7 Conclusions

I started from two procedures used in industry, namely metal coatings and friction stir welding with rotating electrode. As a result of the research conducted in this paper, I succeeded to transfer the knowledge and cases analyzed in this new technological process (which can be used in constructions) to the corrective maintenance of the roads wear layer.

The mathematical evaluation of the parameters and carried out experiments highlighted the efficiency of the method and research. The results communicated by CESTRIN laboratory (analysis of the deposited bitumen) revealed that after sealing the crack (fig. 5.31), the deposited bitumen does not lose its properties, following the passage from solid state to plastic state (table 5.10).

Figure 5.31. Crack sealing in the roadways

Compared to the current expensive methods, requiring skilled labor, the technology and the equipment developed during the thesis preparation allow the development of a new technical concept for *sealing the cracks* in the roadway, using a new method for roads maintenance. This concept has the advantage of significantly reduced costs; also, the workforce has minimum qualification.

The new concept developed in the research paper, based on a technology used in metal processing, is an efficient tool for increasing the operation time of the national roads, reducing the material and labor costs, with a very good impact on the environment because the technology is environmentally friendly.

CHAPTER 6

FINAL CONCLUSIONS AND PERSONAL CONTRIBUTIONS

6.1. General conclusions

Establishing the moment of maintenance decision allows to keep the factors that determine the roads degradation within the range of the parameters accepted by the technical regulations in force. The research conducted during the thesis elaboration led to the development of a new technology and an equipment prototype able to seal more easily the existing cracks of the roadway.

The idea of this research started from the analysis of the welding and coating process by friction with a rotating electrode (applied in industry); after the experimental tests performed at UPB and SC CESTRIN SA, I succeeded to make a prototype equipment and a bitumen electrode with added plastic and rubber powder, to bring a technical novelty in constructions field (corrective maintenance). The experiments with this procedure highlighted the efficiency of the technology.

The research continued the line of the preoccupations from the doctoral period, taking into account the dynamics of the development of the technical solutions at international level.

The research works and the technologies proposed in the doctoral thesis make possible an immediate solution of some problems (the degradations) of the road wear layer. The operating principle of the equipment developed as a result of the research is easy to use, does not require highly skilled/special labor force and involves low maintenance costs. The information taken over after the application of the technological processes helps to establish the future approaches, if they are registered in a digital management system (digital maps).

6.2. Personal contributions

A series of personal and original contributions were made during the elaboration of the doctoral thesis, which can be summarized as follows:

a) theoretical contributions:

- creation of an instrument for determining the coefficients of the model using a factorial experimentation program, in which the variables take a limited number of values or levels. In the case of two-level factorial programs, frequently used for first-order models, the number of tests is 2^k, where k is the number of independent variables. The entire factorial program on the basis of which the coefficients and exponents are estimated includes 8 tests. In order to do the tests, it was used the P1.1 type fractional factorial program with $2^{3-1} = 4$ tests and 2 tests replicated in the center of the experiment;
- systemic study of the sealing process by the method of deposition with rotary element;
- research on the influence of some factors on the average temperature from Tc contact surface and the deposited material volume Vd;

- analysis of systems with large surfaces and determination of the characteristics that require monitoring and that are decisive factors for the predictive, preventive or corrective maintenance;
- development of the methodology for evaluation of the functional parameters and technical condition of the systems with large surfaces;
- implementation of the digital maps, basis of the preventive maintenance strategy;
- introduction of a new concept, namely - *Preventive and predictive maintenance of road structures* - maintenance that allows the forecasting /anticipation of making corrective maintenance works, following the recording of the volume of goods transported in the unit of time per kilometer traveled and the monitoring of the number of shocks that a motor vehicle has per 1,000 m traveled.

b) experimental contributions:

- the creation, research and implementation of a high-performance technology for sealing cracks in the roadway, which is a different technology from the current one, as it is simple, cheap, involves a low-skilled labor force but has a high yield and productivity;
- introduction of a new method for cracks sealing; this method combines the two methods existing nowadays – hot clogging and cold clogging – and improves both the costs and the quality of the clogging/sealing works executed;
- implementation of a new and modern technology for experimenting with the process of cracks sealing in the roadway by using a new experimental equipment, with high performances, which can be used by low-skilled personnel;
- estimation of a vehicle weight by monitoring the dynamic torque of a heat engine (published paper). The results of the research provide the motor vehicles manufacturers with the data needed to develop an intelligent system for continuous monitoring of the weight, with low costs, without involvement of the driver, with possibilities to monitor permanently by GPS the weight, parking and goods loading/unloading. This system brings benefits to road authorities and to the transport system in general, by constantly monitoring the weight during traffic;
- carrying out a scientific study focused on analyzing the roughness of asphalt surface of the wear layer, using the on-the-market current instrumentation, namely a thermal imaging camera for which I found new uses. This scientific study will allow the checking of roadway roughness, with minimum costs and average qualification of the necessary labor force. Thus long-term benefits are obtained in terms of maintenance of high-risk asphalt surfaces (published paper; the work principle is in experimentation progress at CESTRIN SA);
- introduction of the concept regarding the optimal moment to perform clogging works consistent with the national technical regulations in force, in order to obtain maximum effects in terms of cost-benefit ratio;
- dissemination of the results of the theoretical and experimental research by publishing a number of 5 scientific papers from the doctoral thesis field; presentation of a paper at the

National Scientific Conference ICMAS 2018, within the “Politehnica” University of Bucharest.

6.3. Subsequent directions of research

Given the present technology that makes available various programs to the carriers and to those who take care of roads infrastructure, I consider a permanent interconnection, taking into account that the motor vehicles will be autonomous in the future (automated and intelligent, they will no more depend on the human factor). The safe driving will depend on the information collected from the asphalt carpet and on the guiding signals constantly transmitted by the smart panels. In this way, the diminution of transport costs will be correlated with the reduction of traffic risks and the maintaining of road infrastructure characteristics for a well-defined period.

In the next period, I will study the evolution of some programs developed by transport companies and by manufacturing companies, in order to integrate them with the development potential of the sensors in road structure, as follows:

- real-time communication between vehicles and integration with the information transmitted by the road infrastructure (fig. 6.1).

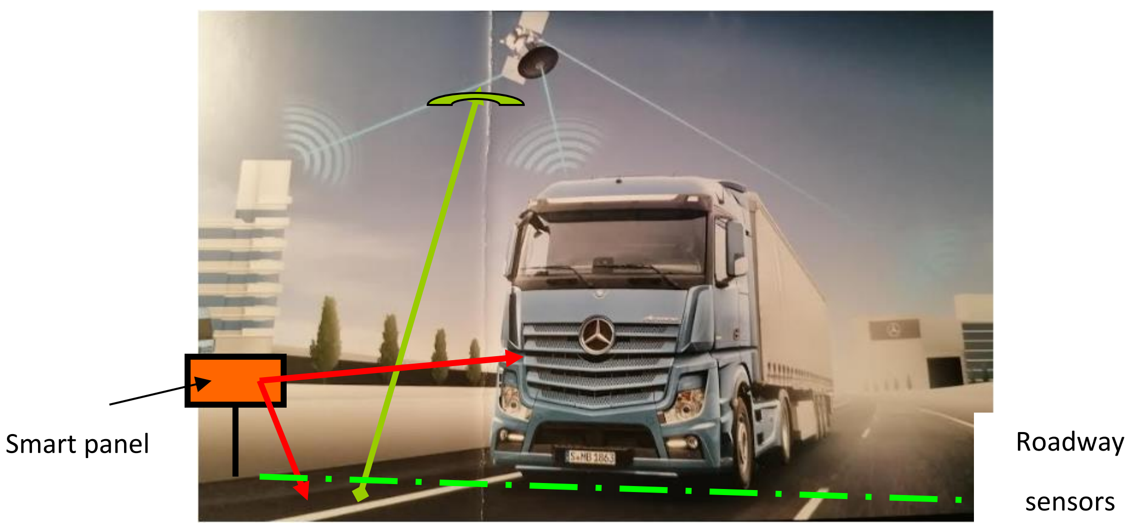


Figure 6.1. Communication systems

- real-time self-diagnosis of the motor vehicle and restoration of the mobility, namely harmonization of the travel speed with the information sent by the smart panels located along the road infrastructure and the communication with the sensors assembled on the means of transport. Consequently, the force resulting from braking will be used to charge the batteries of the vehicle or will be transferred to an energy collecting equipment installed at the side of the road, (fig. 6.2);

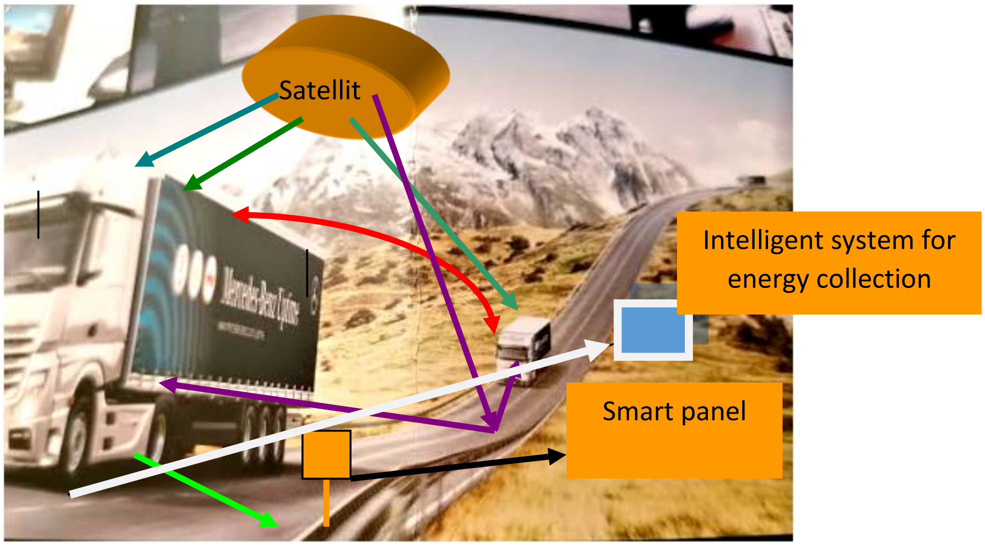


Figure 6.2 Connection between motor vehicle and roadway

- remote diagnosis of the technical problems of the vehicles using the road system, based on the data received from the smart panels and road sensors (fig. 6.3);

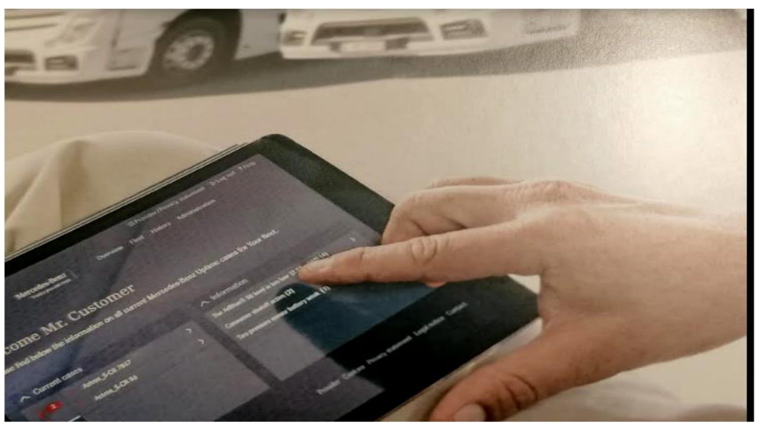


Figure 6.3. Remote diagnosis of the technical problems of the motor vehicles

In the future, the intelligent vehicles will receive real-time information regarding the aspect and construction of the roads, the structural and geotechnical behavior, the drainage systems, the signals system. All these can be combined with behavior patterns and predicted traffic flows, with plans for incidents management and the operational stage of transport, with real-time flows in terms of traffic intensity.

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