

BOGDAN ŻÓŁTOWSKI\*

## Diagnostic investigations of critical technical systems

### Key words

Diagnostic system, technical condition, safety, comfort, dynamic state.

### Słowa kluczowe

System diagnostyczny, stan techniczny, bezpieczeństwo, komfort, stan dynamiczny.

### Summary

This article shows the results obtained during the implementation of a portable diagnosis system to the maintenance routines of the passenger transport vehicles and permanent track of the Metro train, which made it possible to evaluate such aspects as safety, comfort, and the technical condition of the track-vehicle interphase. The reports given in this evaluation allowed the identification and the arrangement of the track sections according to its technical condition, thus relating the track and vehicle condition parameters to the estimators connected with the passenger transport vehicle dynamics.

## 1. Introduction

The manufacturers of the means of railway transport invest vast amounts of money in the construction of fast, safe, comfortable, and efficient passenger transport vehicles. The methods and means of modern technical diagnostics allow maintaining the ability of the means of railway transport through constant monitoring of their technical state. They also allow examining the performance of requirements determined for the means of railway transport in the range of effective safety and comfort standards.

---

\* University of Technology and Life Sciences, 85-796 Bydgoszcz, ul. Prof. S. Kaliskiego 7, Poland, tel. 052 3408283, bogzol@utp.edu.pl

Accepting the vibration signal as the basis of the description and examination of the dynamic state changes of the railway transport system at work, the state of operation, safety and comfort, state changes of chosen assemblies of the railway system, and state changes of the foundation and railway tracks were evaluated.

During the realisation of separate tasks in this work, we used the available, and newly created, procedures for diagnostic signal acquisition and processing for state evaluation. We also created and practically verified the method of measuring point selection for vibration diagnostics, proposed modernised procedures in the range of diagnostic sensitivity examination and boundary value determination for measured signals, verified chosen diagnostic models, and analysed chosen prognosis methods for the needs of the next diagnosis date determination.

In the range of statistic handling of measuring data, we used available but modernised procedures of MATLAB, EXCELL, STATGRAPHIC software, examining the correlations, regressions, decompositions, models – everything at the stage of making diagnostic conclusions. For the detection and location of damages, we used new procedures of the Principal Component Analysis (PCA) methodology and the Singular Value Decomposition (SVD) method [3, 7, 8, 11].



Fig. 1. Cars of metro train on the route  
Rys. 1. Pojazdy pociągu metra na trasie

The length of the power engine is about 22.8 m. All the vehicles have the width of 3.2 m and height of 3.8 m (the height to the roof without the pantograph). Each car of the vehicle is based on two trucks of two axles through four pneumatic cushions, which maintain the settled height of the vehicle regardless of the load. Two trucks of the power engines have a power transmission system on each axle, consisting of a transmission and an electric engine, the latter being hung on a special construction. The supply of compressed air to the unit consisting of three individual cars is realised by a piston compressor. Each car is connected with a short connector that can be removed in a workshop. One connector with a bumper is placed at the end of a car, which allows connecting cars into sets. The damages to the wheels of a railway system most often undergo ability tests in the effective planning-preventing exploitation system. The supervision of the technical state of wheel-rail system has the following parameters:

- Nonalignment,
- Radial aberration,
- Circularity,
- Impurities,
- Waviness,
- Flatness,
- Surface loss (spalling), and
- Material loss.

The most often encountered damages stemming from the wheel-rail cooperation are flatness (due to braking and lack of greasing of the vehicle), periodic nonalignment, and circularity. The tasks and responsibilities of the safe railway system of the METRO system are guaranteed by the modern railway traffic supervision system of METRO.

## 2. Railway car dynamics study

The description and determination of basic parameters for a multi-criteria safety, comfort, and state change system for railway cars mainly requires the estimation of reactions in motion between the wheel and the rail, as well as the dynamics of car motion, which is included in the analysis and synthesis of the dynamic state of the railway car. Bilateral reactions between the moving object and the base affects the vibrations of the rolling stock and the power transmission system and the body.

Vibroacoustic effects – vibrations and noise – present during the vehicle's motion on railway tracks are the source of information on the dynamic state, running comfort, and safety. Source identification of those effects is not always easy. There are geometric irregularities appearing on the elements of the vehicle and track during their use, which can cause transverse displacement and the inclination of the vehicle, longitudinal displacement, swaying, snaking, etc., which are spread onto frames of the truck, and then onto the car (Fig. 2).

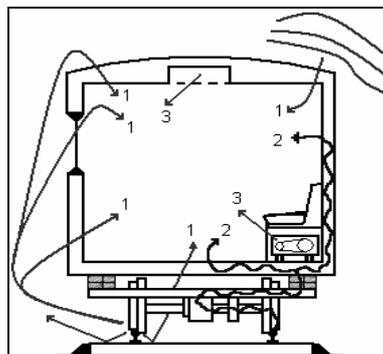


Fig. 2. Lines of noise and vibrations transmission to the passengers

Rys. 2. Oddziaływania hałasu i drgań na pasażerów

For the dynamic analysis of railway cars in specific exploitation conditions, different complex computer programs have been used, such as Vampire, Adams/Rail, Gensys, Simpack, and Miniprof Wheel And Rail (Fig. 3).

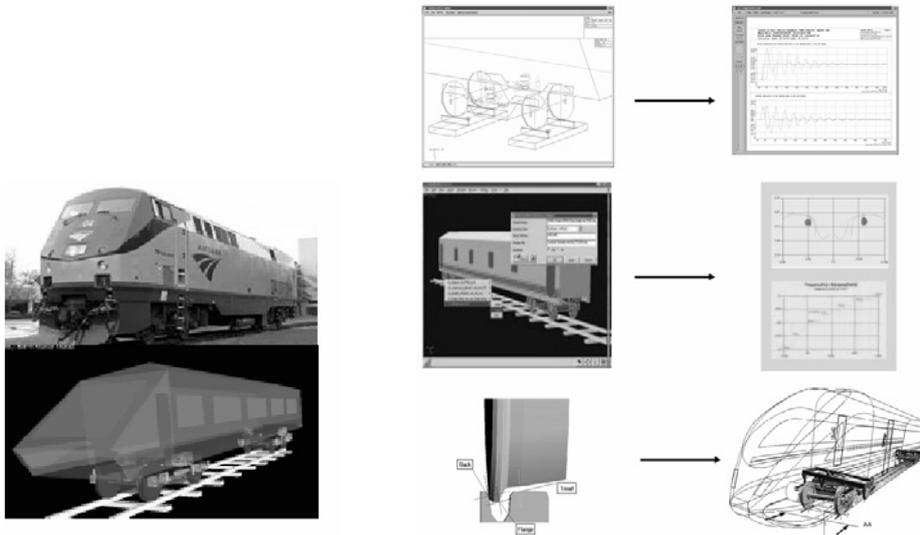


Fig. 3. Example of dynamic modelling for railway engineering  
 Rys. 3. Przykłady modelowania dynamiki pojazdów szynowych

Fig. 4 shows complex computer models created and used for the running dynamics analysis of a railway car.

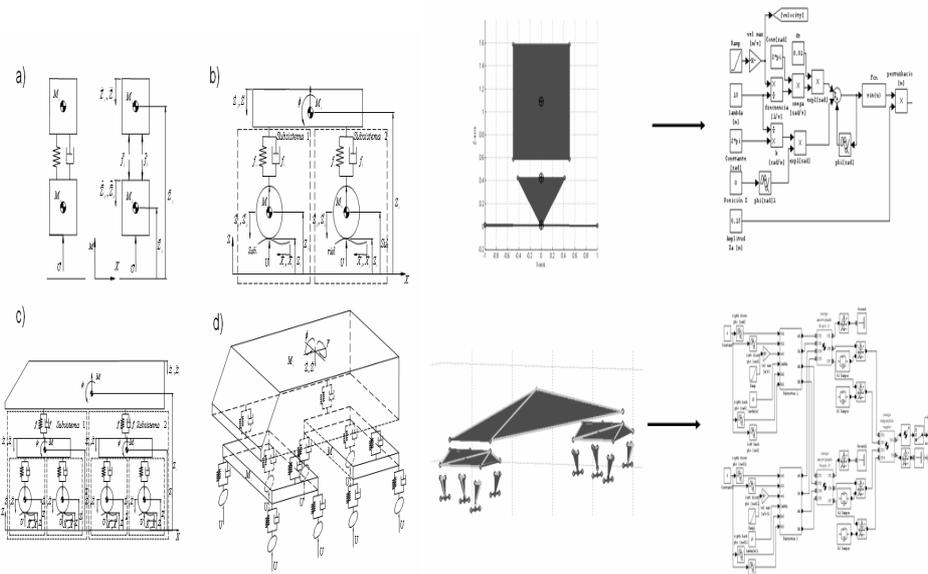


Fig. 4. Computer models for train dynamics testing  
 Rys. 4. Komputerowe modelowanie dynamiki wagonu

These models are described with the use of physical parameters, such as damping, mass and rigidity; therefore, they should contain real values of these parameters. The determination of these parameter values takes place at a special laboratory station.

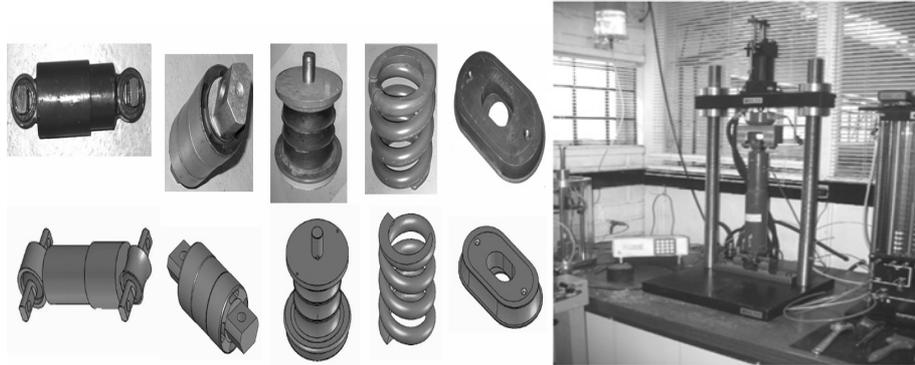


Fig. 5. Physical parameters estimation for train elements  
Rys. 5. Estymacja fizycznych parametrów elementów wagonu

Computer models should reflect physical objects as well as possible; thus, each simulation needs to be verified experimentally. The experimental manner of free vibration frequency determination for a railway car of METRO (empty and loaded), for the purpose of this work, was carried out with the help of a research team (GEMI).

### 3. Running safety and comfort

In order to achieve the reliability and readiness of a system, and to lessen the risk of derailment of a train during its exploitation, there is a need to implement the modern technical diagnosis method, which allows maintaining the life cycle through constant monitoring of the technical state, which determines the fulfilment of running safety and comfort requirements for transportation systems.

Each new railway system is evaluated in the aspect of running safety and comfort through measuring acceleration and forces on different masses of the railway car. The existing norms for the evaluation of these systems present procedures for the acquisition, register, analysis, and comparison between the dynamic measure and boundary value.

In order to evaluate the vehicle's safety, it is necessary to install sensors to determine measurements connected with the train's motion dynamics. The UIC – 518 norm describes procedures for safety evaluation and indicates two measurement methods which allow the determination of relations between the values of vertical forces  $Q$  and shearing forces  $Y$  present during wheel-rail cooperation.

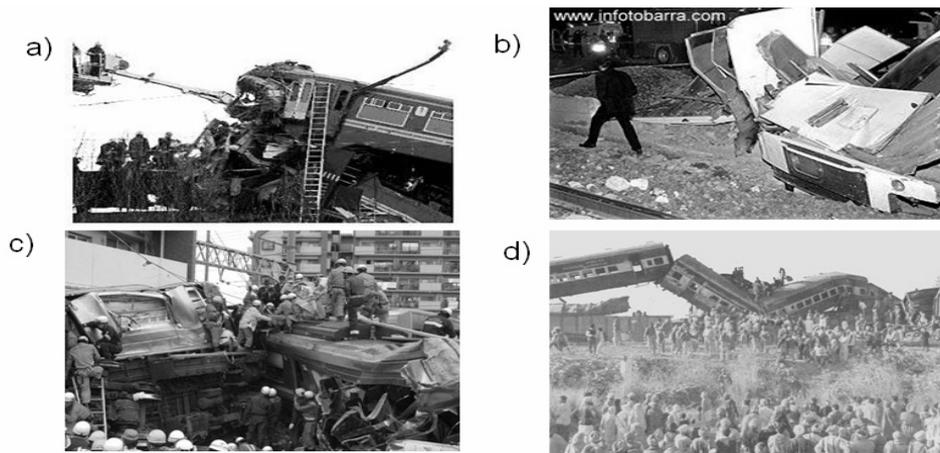


Fig. 6. Train crashes: a) Precot, Belgium - 2001, b) Tobarra, Spain - 2003, c) Amagasaki, Japan - 2005, d) Fatehgarh, Punjab, India - 2000  
Rys. 6. Przykładowe wypadki pociągów

According to the general rule, safety in the train is evaluated on the basis of derailment criterion through wheel displacement values on the upper surface of the rail. The distribution of vertical and shearing forces illustrating the presented relations is show in Fig. 7.

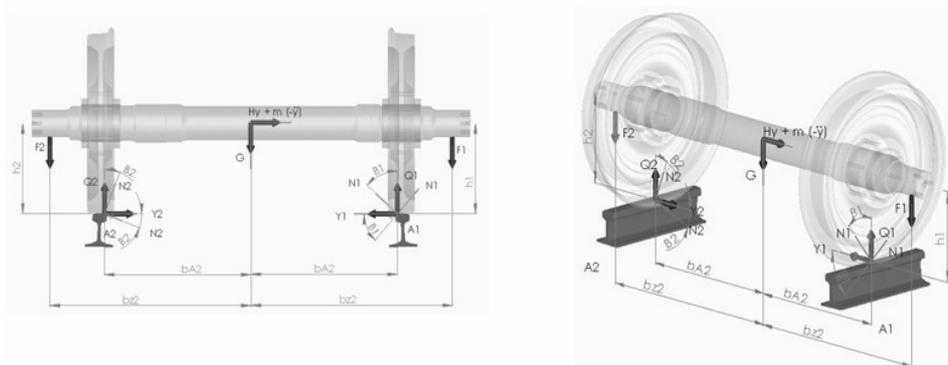


Fig. 7. Force distribution of the wheel-axis set on the rail  
Rys. 7. Rozkład oddziaływań siłowych w układzie koło-szlina

There are different methods in the world used for measuring vertical and shearing forces present during wheel-rail co-operation. One of those methods is a Swiss SBB method, which consists in installing extensometer sensors on the rail's surface between two sleepers, and for result register, a proper configuration of a Wheatstone bridge is used (Fig. 8).

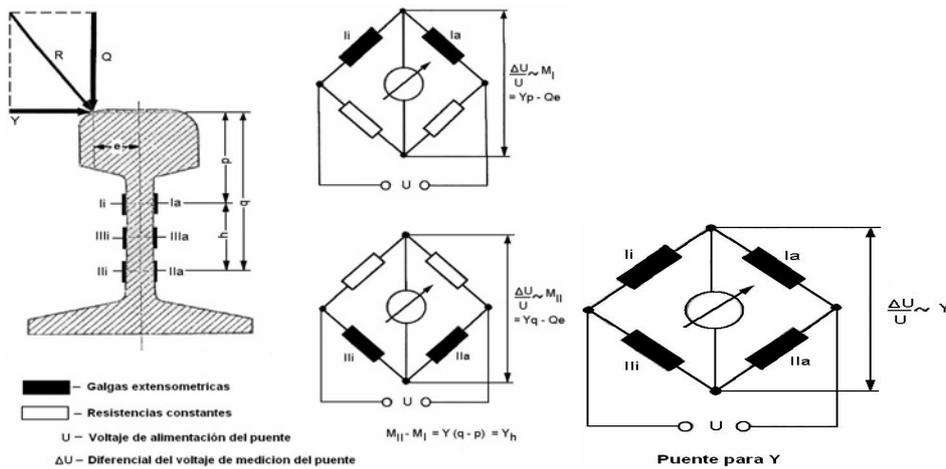


Fig. 8. SBB Method for force measurement  
 Rys. 8. Metoda SBB pomiaru sił

The presented method was used during the research for measuring reaction forces between the wheel and rail, which according to the subgrade quality exploitation data, allowed drawing cause-and-effect conclusions for the needs of the constructed railway cars' state evaluation system.

There are many practically used terms concerning comfort in railway transport, such as passenger comfort, running comfort, running quality, and running indicator. Running quality is affected by physical and human factors, as well as the car's dynamic motion. While running comfort and running quality indicators contain only dynamic parameters of the car's motion. Most often they are acceleration and the linear changes of the railway car motion; and these parameters are normalised in available international norms.

Passenger transportation vehicle comfort is evaluated on the basis of the UIC - 518 norm, considering the following conditions:

- The implementation on trial lines (linearity of the track, geometric parameter quality of the track, velocity, lack of inclination, etc.),
- The geometry of wheel-rail contact,
- Measures connected with the vehicle's dynamics,
- Conditions for automatic and statistic data processing,
- Evaluation of dynamic measures, and
- The boundary values of comfort indicators.

Besides the norms of comfort evaluation of railway vehicles, in which comfort is most often described with the use of acceleration, there are supplementary norms that describe the noise level caused by the train inside and outside the vehicle. It is recommended that noise level research is carried out according to the following options:

- Noise level measurement inside the vehicle when running,
- Noise level measurement inside the empty vehicle during standstill,
- Noise level measurement outside the vehicle when running, and
- Noise level measurement outside the vehicle during standstill.

Figure 9 shows an example of noise level measurement inside and outside the car.

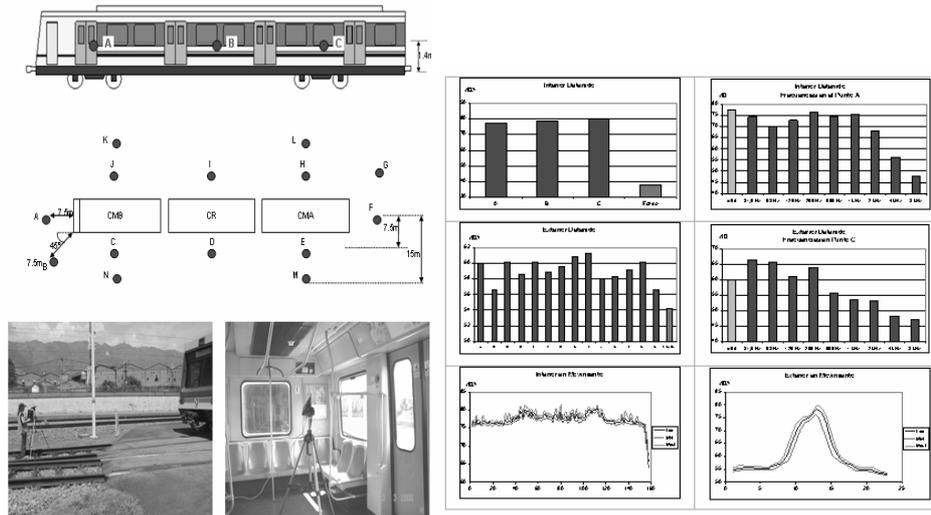


Fig. 9. Noise level measurement inside and outside the railway vehicle  
Rys. 9. Poziomy hałasu wewnętrznego i zewnętrznego wagonu

For the practical uses of comfort evaluation of METRO train cars, the following procedures were used: the evaluation of the influence of vibrations on the running comfort with the use of the UIC – 518 norm, and the evaluation of the influence of noise level on passenger comfort with the use of APTA norm.

To evaluate the comfort, seven estimators for passenger cars need to be determined based on the measurement of vertical and transverse acceleration. They are:  $y_{*q}$  (99,85%),  $y_{*q}$  (0,15%),  $sy_{*q}$ ,  $y_{*qst}$ ,  $z_{*q}$  (99,85%),  $z_{*q}$  (0,15%) and  $sz_{*q}$ . Ride comfort evaluation estimators are determined both for straight and curved sections on the route of a passenger transport vehicle [1,7,8,9].

The presented considerations from the range of railway system safety and comfort, as well as norms connected with their evaluation, gave the basis for creating procedures to conduct measurements of velocity in railway cars and the noise level inside and outside the passenger vehicle. The manner of data acquisition and processing for safety and comfort indicator calculation, as well as valid boundary values, were further used in the research of METRO railway cars.

#### 4. Methodology of train cars diagnosis

The realisation of the main task of the technical diagnosis of train car system requires the determination of relations between the state features and signal parameters. Therefore, the choice of state features (necessary and available) and signals with their estimators for the examined cars has to be made. From the relations present between them, all the necessary criteria values for the safety, comfort, and system changes of the technical state are determined for the examined railway system – Fig. 10.

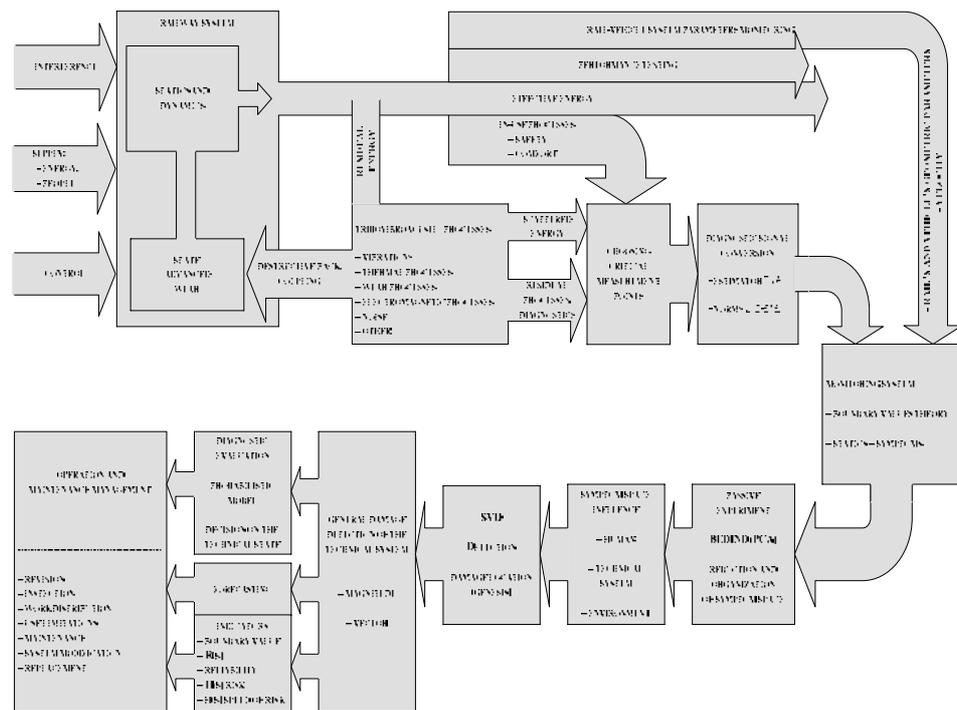


Fig. 10. Methodology of METRO railway system testing  
Rys. 10. Metodologia badań systemu transportowego metra

The methodology of the conducted research is based mainly on the UIC–518 international norm, which describes rail vehicles working conditions for safety and comfort research, such as the vehicle’s velocity, the state of the rail, the object’s dynamic and static state, etc. The research was realised in real exploitation conditions of the transport system and were carried out on 16 trains. In the research, the newest methods of the measurement and description of the state of the train were used, as well as available modern means and methods for the object’s dynamic state parameter evaluation. Also, the means of the acquisition, processing and diagnostic conclusion of the changeable ride quality pa-

rameters of the train are the newest achievements in the field of technical diagnostics of machines.

In the range of research considerations, many original procedures facilitating the realisation and description of researches were created, including the following:

- A method for choosing measurement points for measured signals;
- Methods for determining boundary values for signal estimators;
- The methodology of information reduction for passive experiment testing – amended methodology of Principal Component Analysis PCA for the size reduction of symptom observation matrix;
- The multidimensional graphic method of vector and the author’s own value presentation;
- A decomposition method according to the special SVD (Singular Value Decomposition) values for damage detection and location;
- A technical state evaluation probabilistic model;
- A method for symptom reliability determination for the examined technical system;
- A method for determining the indicators of train exploitation quality; and,
- A method for forecasting for determining the next date of diagnosis.

Diagnostic conclusions leading to a pertinent diagnostic decision requires the association of good state features describing the object’s structure with the damage-oriented symptoms of the state represented by valid diagnostic signal estimators. Therefore, the acquired data needs to undergo various processes during recording, information selection, the extraction of information on the state in boundary value determination, modelling, reliability and risk determination, or the optimisation of further diagnosis dates.

A large quantity of diagnostic information from the railway subgrade testing, noise and vibration testing of the railway system, underwent a statistic process (BEDIND, PCA, SVD, cause-and-effect relations modelling) within useful information extraction as well as for the need of the determination of basic indicators characteristic for the exploitation quality.

## 5. Research results

To examine the running safety and comfort, a monitoring system was installed, which allowed acquiring and registering the data: vibration acceleration, forces and velocity of the vehicle. The sensors of acceleration were installed on the spring suspended mass of the train, i.e. the wheel-axis set, truck frame and the car of the vehicle. The force sensors were placed at the level of the guiding truck, and the velocity signal was provided from the control system of the railway unit. The configurations of sensors, sampling method, filtering and statistic calculation of estimators, were carried out according to the rules of the UIC

international norm. The measurement on each passenger vehicle was carried out in real exploitation conditions, where the monitoring system continuously registered data from different journeys of trains (Fig. 11).

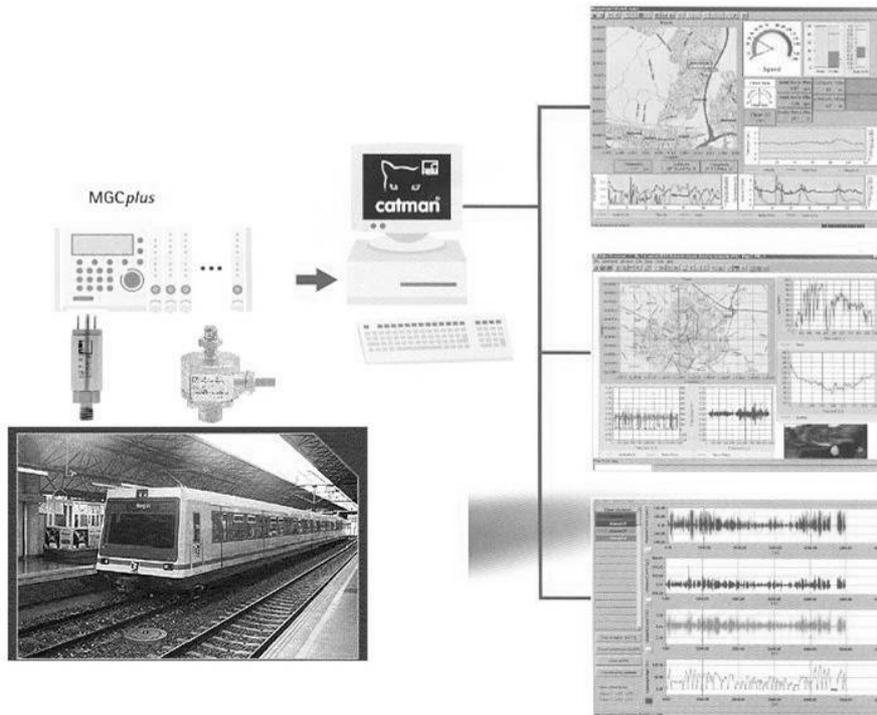


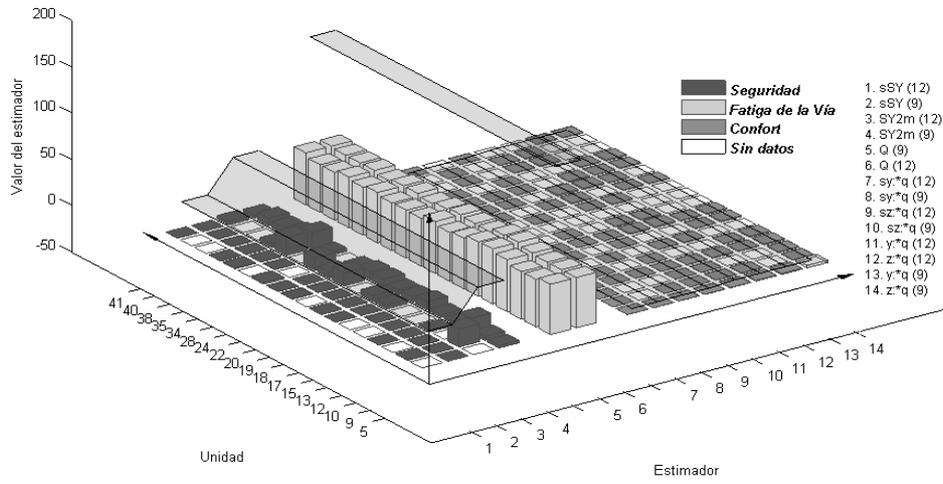
Fig. 11. Measurement System for evaluating the safety and comfort of METRO vehicles  
Rys. 11. System pomiarowy bezpieczeństwa i komfortu jazdy pociągów metra

For the research, the following data acquisition elements were used:

- 4 force sensors HBM U2B/100;
- 8 one-way acceleration sensors HBM B12/500;
- MGC Plus equipment of the HBM company;
- 8 interface cards between MGC Plus and CATMAN program type AP810;
- 4 cards for processing data from force sensors, type ML801;
- A current generator of 110-220VAC 1KVA;
- A voltage regulation system UPS 120Vac/60Hz;
- A computer with CATMAN (5.0 R3) software of the HBM company.

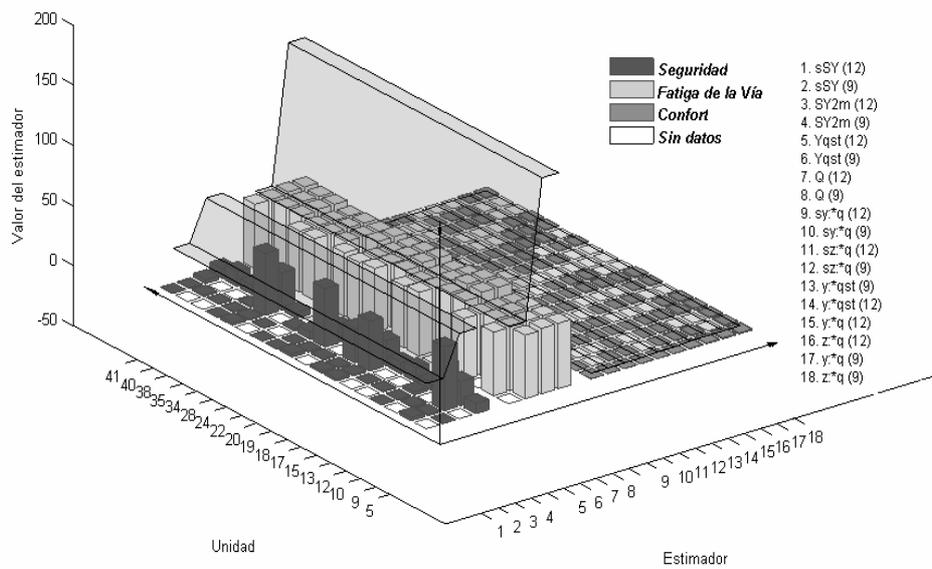
The above elements allow acquiring very complex information necessary to implement the UIC-518 norm in the examined railway system. As the result of UIC-518 norm implementation, statistical reports on the car's safety and comfort evaluation, as well as the track usage, have been created [2, 4, 8, 10, 12]. Example results of the research are shown in the Fig. 12.

Ride in the north-south direction (Niquia – Itagüi)  
Straight sections



The implementation of the UIC-518 norm on straight sections

Curves of a large radius



## The implementation of the UIC-518 norm on curved sections of a large radius

## Curves of a small radius

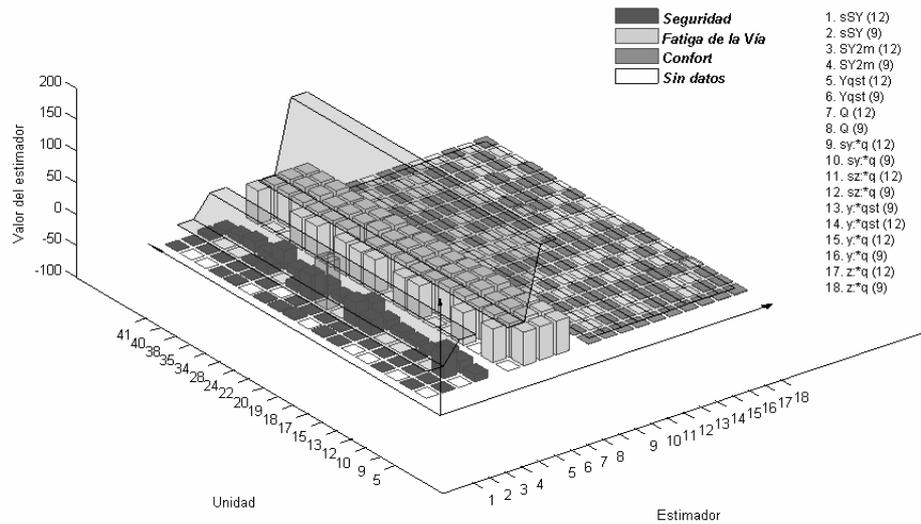


Fig. 12. The implementation of the UIC-518 norm on examined sections  
Rys. 12. Wyniki badań wg zaleceń normy UIC-518 dla wybranych sekcji

The results of the research of the technical state characteristics of the railway subgrade, as well as many vibration parameters and noise, are the result of using many specific procedures and algorithms of technical diagnostics. The software for data processing, built based on available procedures in different programs in the field of acquisition, processing, evaluation and storage, was created for the need of storing all data from 17 examined objects.

The results of the statistical research of a rich informative material from METRO trains provided basic relationships and values, being the basis of the constructed multi-criteria system for the evaluation of running safety and comfort of METRO trains.

## 6. Portable diagnostic system – PSD

The realisation of all the tasks allowed the preparation and construction of a portable diagnostic system. PSD allows evaluating the safety and state of comfort, as well as, with the help of estimators related to safety and comfort evaluation, enables damage detection in the wheel-rail system all along the railway route. It allows optimising all the maintenance actions for cars, the maintenance

of the track, wheel-rail system co-operation evaluation, giving premises to use the strategy in accordance to the technical state [1, 3, 9].

PSD connected with the central traffic control system is a system managing all the information connected with the maintenance of the technical state of the cars, wheel-rail system, track, and the whole railway system in general. Saved in the PSD, the history of the state of all the straight and curved sections as well as the wheels of the passenger vehicle, allows analysing the data, comparing them to the measured estimators boundary values, forecasting state changes and related operations, maintenance, and investment.

The construction of PSD stems from the range of tasks to be realised and diagnosis procedures based on the UIC–518 international norm which possesses all the procedures for passenger transport vehicle testing from the point of view of its dynamic behaviour for track wear evaluation, and the safety and comfort of the ride in natural conditions. Modules of which PSD is made are as follows:

- Sensors module,
- Signal processing module,
- Safety and comfort evaluation module,
- Wheel-rail technical state evaluation module,
- Damage detection module,
- Auxiliary decision-making module,
- Forecast module, and
- Presentation module.

For example, the damage detection module in PSD contains the following tools:

- Monitoring the values of safety and comfort estimators,
- Monitoring the values of frequencies which describe wheel-rail co-operation,
- The detection of maximal forces on the tested track, and
- Monitoring the values of shearing forces generated by railway switches on the passenger vehicle.

The decision-making module is based on the analysis of the correlation between the UIC–518 norm estimators, which evaluate the comfort and safety of the vehicle, and the track's geometric parameters for the tested railway system. The module additionally receives information provided from the safety and comfort evaluation module and wheel-rail technical state evaluation module. This module distinguishes track sections that do not meet the requirements of running safety and comfort in the face of requirements stated by the UIC–518 norm.

The presentation module is an interface between the user and the PSD system. All the information from separate modules is placed there. It is connected to the traffic control system in the company. The module is a safety system that has access to the database, data loading forms, user help, reports, and report generation in Spanish and English.

Fig. 13 shows the initial PSD screen where the upper window allows access to all of the modules and functions. The program has a safety system which, through the necessity of giving one's name and password, does not allow unauthorised personnel to access the program.



Fig. 13. PSD main screen  
Rys. 13. Widok ogólny

PSD is the basic tool for strategy implementation according to the technical state in the METRO enterprise.

The suggested METRO railway technical state research system, has been adjusted to the exploitation natural conditions; and it uses estimators both advised by the UIC-518 norm and new vibration state estimators. Also, the final product of the work, in the form of the portable diagnostic system, implemented in the METRO railway exploitation system, allows the implementation of the exploitation of the diagnostic system in METRO enterprise.

## 7. Summary

In the research of this work, we considered the problem of creating and practically verifying an evaluation system for running safety and comfort of METRO trains. The created evaluation system strays in its range from the requirements of the UIC-518 norm in the field of requirements concerning the conditions of research performance and range. In this work, we have performed the evaluation of motion safety and running comfort due to the requirements of the UIC-518 norm for railway vehicles in real usage conditions, and not on special rails or fields proposed by the manufacturers of these transportation systems.

The proposed system of state examination of METRO was adjusted to real exploitation conditions, and it uses both new estimators of the state of vibration and those recommended by the UIC-518 norm. Furthermore, the final product of this work, in the form of a portable diagnostic system implemented into the exploitation system of METRO trains, allows the introduction of the exploitation diagnostic system into the METRO enterprise in Medellín.

The realisation of detailed tasks of the presented procedures allowed the creation of a multi-criteria system for the evaluation of the state evaluation of METRO trains.

## References

- [1] Castaneda L.: Monitoreo Multidimensional de la Interfase Vía-Vehículo de un Sistema Ferroviario. Congreso Internacional de Mantenimiento – ACIEM – 2007, Bogotá, Colombia.
- [2] Castaneda L., F.: Multicriterial system for evaluating the safety and comfort in railway vehicles. Ph.D. thesis, UTP, Bydgoszcz 2007.
- [3] Żółtowski B.: The Fundamentals of Machine Diagnostics (in Polish). ATR, Bydgoszcz 1997.
- [4] Żółtowski B., Castaneda L.: Portable diagnostic system for the metro train. Diagnostyka, nr 1(37), Olsztyn 2006, pp. 39–44.
- [5] Żółtowski B.: Energetic Measures in Machine Diagnostics (in Polish). BALTECHMASZ, Kaliningrad, 2006, pp. 290–302.
- [6] Żółtowski B.: Diagnostic system for the metro train. ICME, Science Press, Chengdu, China, 2006, pp. 337–344.
- [7] Żółtowski B., Castaneda L.: Sistema Portail de Diagnostico para el Sistema Metro de Medellín. VIII Congreso Internacional de Mantenimiento, Bogota, Columbia 2006.
- [8] Pantopian N.H., Larsen, J., Unsupervised condition detection in large diesel engines, Proceedings of the IEEE Workshop on Neural Networks, 1999.
- [9] Deng J-L.: Control Problems of Grey Systems, Systems and Control Letters, Vol. 1, No 5, North Holland, Amsterdam, 1982.
- [10] Deng J-L.: Introduction to grey system theory, The Journal of Grey System, 1989, Vol. 1, No 1, pp. 1–24.
- [11] Wen K.L., Chang T.C.: The research and development of completed GM(1,1) model toolbox using Matlab, International Journal of Computational Cognition, 2005, Vol. 3, No 3, pp. 42–48.
- [12] Yao A.W.L., Chi S.C.: Analysis and design of a Taguchi-Grey based electricity demand predictor for energy management systems, Energy Conversion & Management, 2004, Vol. 45, pp. 1205–1217.

*Manuscript received by Editorial Board, July 22<sup>th</sup>, 2008.*

**Badania diagnostyczne krytycznych systemów technicznych****Streszczenie**

Artykuł ten pokazuje opracowane procedury i wyniki uzyskane podczas wprowadzenia przenośnego systemu diagnostycznego do systemu utrzymania pojazdów pasażerskich i trwałości szlaku pociągów metra. System diagnostyczny umożliwia ocenę takich aspektów ruchu, jak: bezpieczeństwo, komfort psychiczny i stan techniczny wagonów pojazdu kolejowego. Sprawozdania oddają ocenę stanu oraz identyfikację i utrzymanie zdolności sekcji szlaku, zgodnie z jego stanem technicznym, wykazując w ten sposób stan szlaku i parametry ruchu pojazdu za pomocą estymatorów związanych z dynamiką ruchu pojazdów pasażerskich.