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SOFTWARE APPLICATION FOR ASSESSMENT THE RELIABILITY OF SUSPENSION SYSTEM AT OPEL CARS AND OF ROAD PROFILES

Lucian ROMAN[1], Adrian FLOREA[2], Ileana Ioana COFARU[3]
[1] Industrial Engineering and Management Department, 'Lucian Blaga' University of Sibiu, lucian.roman@autohaushuber.ro
[2] Computer Science and Electrical Engineering Department, 'Lucian Blaga' University of Sibiu, adrian.florea@ulbsibiu.ro
[3] Industrial Engineering and Management Department, 'Lucian Blaga' University of Sibiu, ioanalogistictop@gmail.com

***Abstract*—**One important goal of auto services consists in the correct prediction of replacement moment for each spare part. Starting by the parts sales analysis from AutoHaus Huber Sibiu, we studied the operational reliability at Opel cars in order to forecast their failure. Analyzing 3358 repaired cars during 12.01.2009 ÷ 31.01.2011 revealed that tie rods and dampers must be replaced quite early, to about 5 years. For increasing the reliability we propose an optimal design solution of the suspension system that finds parameters of stability and comfort under different exploiting conditions minimizing the discomfort during movement. Because the description of mathematical model, of the road profiles, of the optimizations techniques and of the integrating software applications represents extensive information that cannot be exhibited in a single article, in this paper we analyze the reliability of the suspension system, we provide software details and graphical results regarding different implemented road profiles.

***Keywords*—**Reliability, Road Profile, Software Application, Suspension System.

I. INTRODUCTION

LIKE most auto parts, the suspension system components fail, not necessarily because the manufacturing warranty expired, but specially due to wear. The tie rods and dampers longevity is affected by driving conditions. The road profile, the surface irregularities, poor road conditions or minor accidents directly influence the wear of runtime system components, braking and suspension, causing the vehicle malfunction. Deteriorating road quality and speed humps produces a significant stress on the suspension system by increasing the oscillations frequency with large amplitudes. Due to high degree of usage and their importance in ensuring passenger safety and security, experts recommend regular inspection of tie rods. Correct prediction of mean time to failure for each spare part and especially for the suspension system components represents a goal for auto services [1], [2]. From an economic perspective, automotive companies are looking for solutions to reduce costs to remain competitive [1]. Thus, better car reliability is equivalent to increasing customer satisfaction, leading finally to increase the number of sales.

Starting by the parts sales analysis from AutoHaus Huber Sibiu, we investigated the operational reliability at Opel cars exploited in Romania in order to forecast their failure. Analyzing 3358 repaired cars during 12.01.2009 ÷ 31.01.2011 revealed that tie rods and dampers must be replaced quite early, to about 5 years. In order to increase the reliability of vehicles we formulated a design solution of the suspension system for finding the target parameters of stability and comfort in different operating conditions (on different road profiles) to reduce discomfort caused by disturbance factors and to ensure passenger comfort during movement. Because the description of mathematical model, of the road profiles, of the optimizations techniques and of the integrating software applications, represents a laborious work and an extensive amount of information that cannot be exhibited in a single article, in this paper we analyze the reliability of the suspension's system components and we provide software details and graphical results regarding the road types that we will study in the analysis of Quarter-car model with two degrees of freedom [3], the other aspects making purpose for another article.

In our previous work [4], we designed a 3-tier database architecture composed by Presentation, Logic and Database layers and we implemented the Crawler, Database and Data Visualization modules dedicated for OPEL cars' maintenance management. The developed software application was implemented in Microsoft Visual Studio 2012 (C#), .NET Framework 4.5, using Microsoft SQL Server 2012. The Crawler module extracted relevant data from archive of orders with maintenance operations and spare parts. The Database module was responsible for designing the conceptual scheme of database and mapping, performing database queries, being able to handle huge bulks of data. The following tables were mapped in the database: *Cars*, *Orders*, *OperationsList*, *PartsList* and *SparePart*. The Data Visualization module has implemented the graphical user interface that allows data manipulation operations and also the presentation of some results about spare parts, operating mode, etc.

We extended this previous work with two new modules. Based on laborious database SQL queries and with the help of open friendly interface our application graphically presents very important results. Based on quantitative real data collected from AutoHaus Huber Sibiu, the first module determines and illustrates graphically the reliability functions and cumulative probability for failure, the mean time to failure, all regarding the suspension system components. The second allows the configuration of different types of road profiles and the graphical representation of them in two dimensional axis systems.

The organization of the rest of this paper is as follows. In section II we review the basic concepts and reliability metrics that we applied to experimental data retrieved from OPEL car service, emphasizing on suspension system components. Also, it is described the selection menu of graphical users interface that allows to report different reliability graphics, emphasizing software details regarding to export of SQL data to Microsoft Excel using C# and it is shown which SQL queries were most used. Then, it is presented the methodology for operational reliability's evaluation. Section III describes shortly the road profiles according to ISO 8608 standard, formulates the analytical equation used to generate an artificial road profile in order to software implement and provides programming details and graphical results for various configurations. Finally, section IV suggests directions for future work and concludes the paper.

II. Reliability Basic Concepts

A. Reliability indicators

In this paragraph we intend to briefly explain some basic concepts about reliability and review some reliability indicators that we use in our evaluation methodology of operational reliability at OPEL cars. Reliability can be defined qualitatively or quantitatively, as follows:

1) *From qualitative viewpoint the reliability is the ability of a product to operate without failures in a given time interval under specified conditions.*
2) *From quantitative viewpoint the reliability represents the probability of a product to meet certain performance functions without failure, within the time and in the given operating conditions.*

The operational reliability is characterized by the fact that the product's reliability to the beneficiary is established based on in service behavior of a large number of samples over a certain period of time. This process takes into account the complex and conjugated action of internal and external factors, constraints related to real working system, environmental peculiarities and the technical maintenance conditions. We name estimated value of cumulative probability for failure at a certain moment t_i (when ends the *"i"* interval),

$$\hat{\mathbf{F}}(\mathbf{t_i}) = \frac{\mathbf{n_{partial}}}{\mathbf{n}} = \frac{\mathbf{1}}{\mathbf{n}} \cdot \sum_{j=1}^{i} \mathbf{n_j} \tag{1}$$

where n represents the total number of cars that are tracked in operation and finally fails, whilst $n_{partial}$ is the cumulative frequency of failures, and n_j is the frequency of failures occurred during "*j*" interval. Its value is increasing and becomes equal to 1 to the last frame of the series.

We name the relative frequency of in operation vehicles, which is calculated as the one's complement relative to the cumulative probability for failure. It is also known as the estimated experimental reliability because it shows the share of vehicles that were not deteriorated until the end of range "*i*" but which fail during the next intervals. Then, the estimated reliability is obtained with formula

$$\hat{\mathbf{R}}(\mathbf{t_i}) = \mathbf{1} - \hat{\mathbf{F}}(\mathbf{t_i}) \, . \tag{2}$$

The mean time to failure (MTTF) is an extremely important way of evaluation the reliability in safety-critical systems. MTTF represents the length of time a system (component) is expected to last in operation and is rather similar to another related term, mean time between failures (MTBF). The difference between MTTF and MTBF is that while the last is used for systems or components that can be repaired and returned to use, the first is used for non-repairable systems. As quantitative metrics, while MTBF express the proper functioning between any two successive failures, MTTF express how long a system can reasonably be expected to correctly operate, based on specific testing. MTTF is a direct indicator because its size is proportional with the system reliability: a high degree of reliability means a higher MTTF value and conversely. Thus,

$$\mathbf{MTTF} = \frac{\sum_{i=1}^{15} \mathbf{tm_i} \cdot \mathbf{n_i}}{\mathbf{n}} = \frac{\sum_{i=1}^{15} \mathbf{tm_i} \cdot \mathbf{n_i}}{\sum_{i=1}^{15} \mathbf{n_i}} \tag{3}$$

where tm_i is the average operating time of products that fails during the "*i*" interval, from all 15.

B. Export SQL Data to Excel Using C#

Software contribution of this work consists in the two menu options introduced: *View* – that generates and view different road profiles according to ISO 8608 and, *Reports* – which provides statistics relating to the sale of spare parts from AutoHaus Huber Sibiu service, the estimated reliability and the Mean Time To Failure for various spare parts, emphasizing on suspension components. For example, if the user intends to view the estimated reliability of tie rods he selects (see Fig. 1) the sequence of options: *Reports*→*Reliability*→*Tie rods*. At this point, in the application's background based on experimental calculations begin some measurements of damaged parts on running interval ranging between 0 and 150000 km, in quanta of 10000 km. In the first stage using SQL clauses are successively (for each quanta) counted and fetched from *Orders* table and placed in a new line in the Excel table, the number of defective and replaced parts. After repeating the algorithm for 15 times, in the Excel file we may generate suggestive charts similar to those in Fig. 4 ÷ 7.

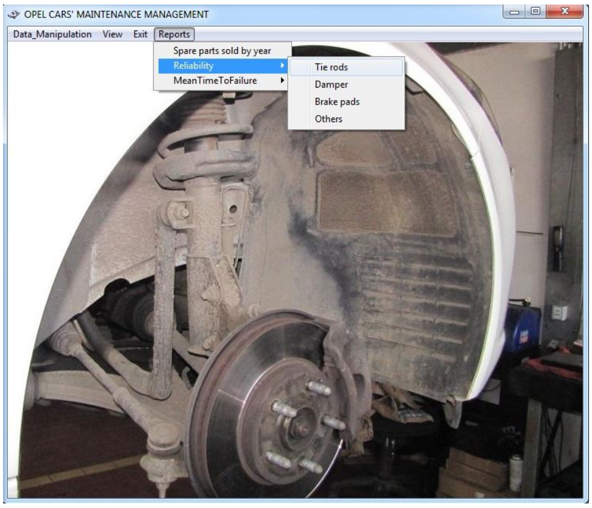

Fig. 1. Select menu to illustrate the reliability for a certain spare part.

From the perspective of software developers, it can be said that the Visual Studio 2012 environment is highly evolved and, with the help of COM objects facilitates data communication between the database tables (in our case *Orders*, *PartsList*, etc.) and Microsoft Word or Excel, but also conversely [5]. Component Object Model (COM) is a mature binary-interface standard for software components introduced by Microsoft for more than 20 years and is used to enable inter-process communication and dynamic object creation in a large range of programming languages. COM represents the basis for several other Microsoft technologies and frameworks such OLE (object linked and embedded), ActiveX, etc.

Summarizing, the Fig. 2 involves the following steps: First, it establishes a connection to SQL Server Compact Edition, creating the connection with the database (using a *SqlCeConnection* object). Then we set the SELECT query (the *SqlCeCommand* object) which determines the number of parts damaged and replaced. A *SqlCeDataAdapter* object makes the connection between the connection component and the SQL command, then it transfer the selected data into a table (*DataTable* object). It will be transferred into a Worksheet object of a Workbook belonging to an Excel application. Using parallel code sections (the *foreach* instruction) each column from DataTable will contribute to generating the header of the new created Excel file. Further, by a similar instruction is parsed each row of the SQL table and inserted as a new line in to the Excel file. At the end of this process the database connection closes and the Excel file is saved to the computer hard disk, facilitating the graphics representation of results (the estimated reliability, MTTF, etc). In order to increase the software application's robustness, we used the *try* and *catch* mechanism. Try-Catch-Finally statements are powerful structure that help the program to be run flawless on most systems. It is a very good error handling mechanism that avoids program's crash in not elucidated situations.

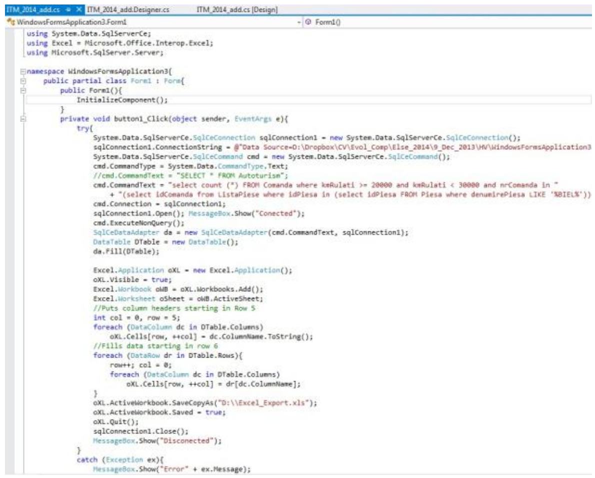

Fig. 2. The source code for generating the *.xls* files in order to calculate the estimated reliability.

In order to find the absolute frequencies of failures expressed in kilometers intervals we apply the next SQL command (repeatedly for each subinterval). The command represents a double nested query composed by an outer query applied to *Orders*, table which knows the IDs of orders treated for different number of km but does not know the name of spare parts from orders, and two inner queries, one that relates the *Orders* table with the *PartsList* table by spare parts IDs on each order, and other applied to *SparePart*, table which maps the name of spare parts with their ID's. Usually, the inner query is also known as subquery, which is a regular query placed within another SQL query (as known as outer query) embedded within the WHERE clause. The inner query executes first before its parent query so that the results of inner query can be passed to the outer query [6].

SELECT COUNT (*) FROM *Orders* WHERE kmRulati >= 20000 AND kmRulati < 30000 AND nrComanda IN (SELECT idComanda FROM *PartsList* WHERE idPiesa IN (SELECT idSpareParts FROM *SparePart* WHERE NameSpareParts LIKE '%damper%'))

C. The evaluation methodology of operational reliability at OPEL cars

In this section we attempt to answer the following questions: What are the most replaced components? Why do these failures occur? What can be done to predict the failures? What solution to apply in order to optimize the system?

In order to answer to first question, in Fig. 3 we present the parts sales analysis from AutoHaus Huber Sibiu starting with 2007 until 2013 focusing on the best sold spare parts.

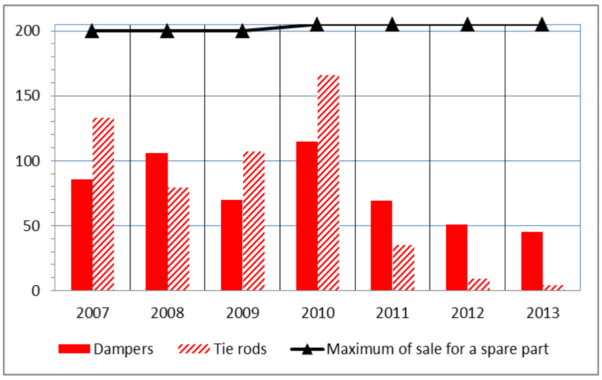

Fig. 3. Spare parts sold by years.

Among all the sold pieces, there were at most six types of pieces that have been sold more than dampers and tie rods. However, all of these are consumables (filters, antifreeze, engine oil, clips, rivets, spark plugs). In conclusion, the main parts to be considered and whose reliability must be studied are the suspension system components: tie rods and dampers. Therefore, further we focus the assessment only on the two components, by analyzing samples of failures on each 10000 km, until 150000 km.

With collected data we complete the following table applying some aggregating formulas and generate the charts from Fig. 5, 6 and 7. In the table generated by our C# software application we already have the frequency of failures occurred during each sample interval (the n_j – parameter in (1)). We compute the cumulative frequency of failures – $n_{partial}$, the estimated value of cumulative probability for failure – $\hat{F}(t_i)$, the estimated reliability – $\hat{R}(t_i)$, and the mean time to failure – MTTF, all these parameters being defined in (1), (2) and (3).

n	271		SparePart=Tie rod		
j	Sample interval [*10000] km	n_j	$n_{partial} = n_{partial} + n_j$	$\hat{F}(t_i) = \frac{n_{partial}}{n}$ F_Tie_rod	$\hat{R}(t_i) = 1 - \hat{F}(t_i)$ R_Tie_rod
1	10	7	7	0.0258	0.9742
2	20	25	32	0.1181	0.8819
3	30	29	61	0.2251	0.7749
.	.	.	.	.	.
.	.	.	.	.	.
15	150	11	271	1	0

Fig. 4. Assessment the estimated reliability based on failure frequencies.

Based on operational measurements, in Fig. 5, 6 and 7 are graphically expressed the histogram with the failure frequencies, the reliability function - R(t), the cumulative probability for failure - F(t) and the mean time to failure - MTTF for suspension system components, reported to tens of thousands of miles.

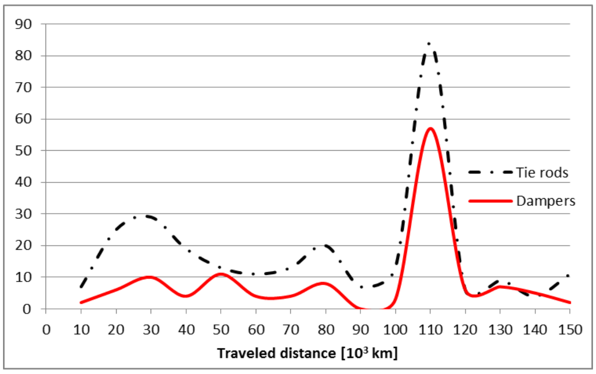

Fig. 5. Suspension system components: failure frequencies.

In our statistics we called as tie rods the following spare parts: inner and outer tie rods, steering rods, anti-roll rods, bushings, ball joints, sway bar links, jam nuts and control arms related. Also, we use the dampers term substituting the following spare parts: damper, bearings, coil spring, buffer, ring and flange related. Of the 3358 repaired cars in service Autohaus Huber Sibiu during 12.01.2009 ÷ 31.01.2011, 271 have damaged due the tie rods and 130 have failed because of the dampers, after a running up to maximum 150000 km. The number of defective dampers is about half of the tie rods and, as the Fig. 6 reveals, the maximum number of failures occurred within the driving range between 100000 km up to 110000 km.

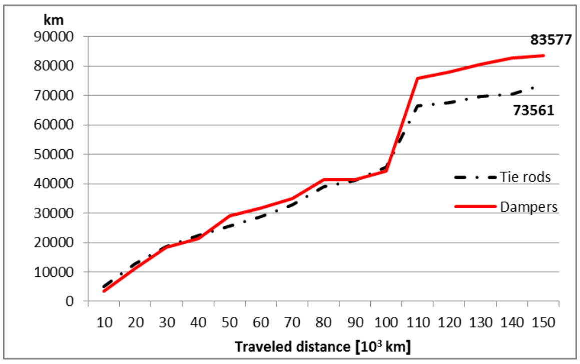

Fig. 6. Suspension system components: MTTF.

Analyzing the results it is observed that the failure of components is done unevenly and the dampers reliability is higher than that of tie rods. The charts illustrated in Fig. 5 and Fig. 7 are correlated. Increasing the number of failures in the range between 100000 km and 110000 km significantly increases the cumulative probability for failure (F) and decreases the reliability function (R).

The results show that the MTTF is about five years of running (estimated time for a travelling distance of 73500 km by a regular driver which runs about 250 km weekly, in the city, which performs yearly about 2000 km in holiday, and makes one or two trips per year outside of the village (about 1300 km). Although the manufacturer does not specify the average lifetime for these types of components, the OPEL experts suggest that these express a too short lifetime (only five years). It is obvious that one cause of failure consists in the road conditions. For example, if one wheel falls into a pothole, the link rod is exposed to a massive shock loading. If this happen in wet and cold conditions when materials used in the ball joint part of the rod are very brittle, then the ball joint becomes vulnerable to water and grit ingress, leading to failure.

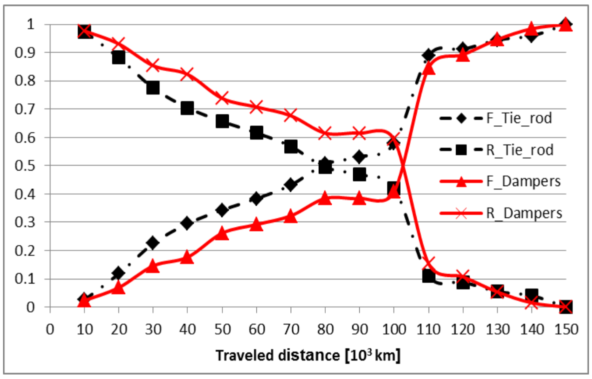

Fig. 7. Suspension system components: the reliability functions and cumulative probability for failure.

III. Generate an Artificial Road Profile

A. ISO 8608 standard basic concepts

The road profile represents the variations in height (unevenness in Europe or roughness in United States [7]) of the road's surface measured along the road on a certain travelled distance. The ISO 8608 standard classifies road profile and describes the methodology to be used for generation the road surface profile [8]. Basic concepts in aforementioned standard are spatial frequency defined as cycles/meter, road profile and Power Spectral Density (PSD). The road roughness profile is described by PSD function of vertical displacements G_d as a function of spatial frequency n, in the form:

$$G_d(n) = G_d(n_0)\cdot\left(\frac{n}{n_0}\right)^{-2} \qquad (4)$$

where n_0=0.1 cycles/m is the conventional spatial frequency set by ISO 8608 and the values of $G_d(n_0)$ is obtained from the Table 1 on the basis of the considered road class. If the car is assumed to travel with a constant speed over a certain road segment of length L, a random profile of a single track can be approximated by a superposition of N ($\rightarrow\infty$) sine/cosine waves [7], [8]:

$$h(x)=\sum_{i=1}^{N}\sqrt{2\cdot\Delta n\cdot G_d(n_i)}\cdot\cos(2\pi\cdot i\cdot\Delta n\cdot x+\varphi_i) \qquad (5)$$

where φ_i is random phase angle uniformly distributed within the $[0, 2\pi)$ range, n_i is the generic spatial frequency value and $n_i = i\cdot\Delta n$; Δn is the discretized step of the spatial frequency and $\Delta n=1/L$, and x is the abscissa variable ranging between 0 to L. Knowing the sampling interval of roads' length (B) it could be determine the number of periodic bumps (N), N = L/B. Substituting (4) in the (5), we obtain:

$$h(x)=\sum_{i=1}^{N}\sqrt{\Delta n}\cdot 2^k\cdot 10^{-3}\cdot\left(\frac{n_0}{i\cdot\Delta n}\right)\cdot\cos(2\pi\cdot i\cdot\Delta n\cdot x+\varphi_i) \qquad (6)$$

TABLE I
ISO 8608 values of $G_d(n_0)$

Road class	$G_d(n_0)$ [10^{-6}m^3] Lower limit	Upper limit
A		32
B	32	128
C	128	512
D	512	2048
E	2048	8192
F	8192	32768
G	32768	131072
H	131072	-

Fig. 8 illustrates a poor quality road full of potholes located on the street where authors live, in Sibiu, but the analysis can be extended to several cities in Romania. It can be analytically described by functions that generate artificial road profile, such as in (6).

Fig. 8. Relatively poor-quality road in Sibiu.

B. Software implementation of road profile

Starting by the analytic expression (6), we will further present software details and graphical results regarding to different type of roads that we will study in the analysis of Quarter-car model with two degrees of freedom. The main C# functions that implement (6) and draw the road are *GenerateRoad*() and *CreateGraph*() (see Fig. 9).

The *GenerateRoad* function has the next parameters:

1) *First, the road type (the k parameter in (6)), as an integer value ranging between 3 and 8, depending on ISO classification. The lowest value means road with minor degree of roughness and the highest value corresponds to very poor conditions road.*
2) *The second represents the range of spatial frequency considered.*
3) *The third parameter consist in the sampling interval (the step size on Ox axis for which is computed the road profile height). The road profile signal is discretized and it is described as a sequence of*

elevation points uniformly spaced. In our work is 0.01m but should be less than 0.0167m. This means that, for drawing the road on a travelled distance of 250m we divide the curve in 25000 points on graphic.

Actually, the function supposes computing the constant factor from (6) and provides as result the array of points for graphical representation with the help of two nested loops. In the internal loop is computed the height of each point by combination of a high number of larger and shorter periodic bumps with different amplitudes, and the external loop repeat the algorithm for 25000 times.

```
using ZedGraph;

private void CreateGraph(ZedGraphControl zgc){
    GraphPane myPane = zgc.GraphPane;
...
    if (roadParams["type"].Equals("random")){
        myPane.XAxis.Title.Text = "Distance (m)";
        RandomRoad road = new RandomRoad();
        double k = Double.Parse(kTextBox.Text);
        double step = 0.01;
        double[] signal = road.GenerateRoad(k, new double[] {0.004, 4}, step);
        for (int i = 0; i < signal.Length; i++)
            list1.Add(i*step, signal[i]*1000);
        hMaxLabel.Text = (signal.Max() * 1000).ToString();
    }
    LineItem myCurve = myPane.AddCurve("",list1, Color.Red, SymbolType.Diamond);
}

public double[] GenerateRoad(double k_p, double[] range_p, double step_p){
//...
    double step = step_p;
    double[] semnal = new double[(int)(L/step)];
    Amplit_ct = n0 / Math.Sqrt(delta_n) * Math.Pow(2, k) * Math.Pow(10, -3);
    for (int x = 0; x < semnal.Length; x++){
        sum = 0.0;
        for (int i = 1; i <= N; i++)
            sum += (double)(Amplit_ct / i)*Math.Cos(2*Math.PI*(double)(i*delta_n)*(x*step)+Psi[i]);
            semnal[x] = sum;
        }
        return semnal;
    }
//...
}
```

Fig. 9. C# source code for generating and drawing artificial road profiles.

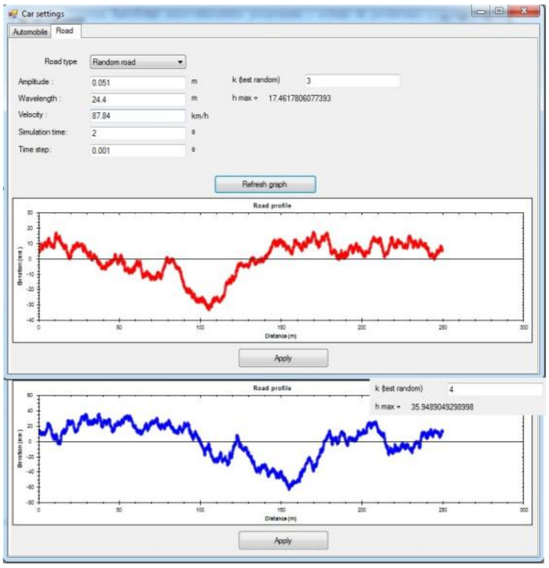

Fig. 10. Artificial road profiles generated for different configurations.

Using *ZedGraph* functions package we realized 2D graphical representation of generated artificial road profiles (see Fig. 10). The *CreateGraph* function has only a single parameter, a ZedGraphControl object. It takes the result provided by *GenerateRoad* function and generates a list of point data structures that connects them by lines of a certain style and of a certain color. Also, the function computes the maximum height of the road. The zoom (in / out) operations can be done using the mouse wheel and the pan operation can be done by clicking the mouse wheel and moving it.

IV. Conclusion and Further Work

With the help of powerful software tools such as Microsoft Visual Studio 2012 C#, Microsoft SQL Server 2012 and ZedGraph package we assessed the reliability of suspension system at OPEL cars and we generated and drew some artificial road profiles. The estimated reliability of suspension system components dramatically decreases in the range between 100000 km and 110000 km. Also, the mean time to failure for these spare parts in the operating conditions from Romania is about five years of running, the MTTF metric predicting the appropriate moment of replacement.

For further work we are concerned to improve suspension's system by optimizing the stiffness and damping coefficients in order to minimize the maximum bouncing acceleration of the sprung mass and minimize the average suspension displacement during movement on roads having profiles like those presented in this work. For solving these issues we have to describe and software implement the mathematical model of suspension with the help of differential equations and to introduce multi-objective optimization methods.

Acknowledgment

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References

[1] J.H. Ellington, *The optimization of General Motors' warranty system by reducing mean time to discover failure*, Master of Science Thesis Dissertation, Massachusetts Institute of Technology, 2005.

[2] S. Söhnlein, F. Saglietti, F. Bitzer, M. Meitner, S. Baryschew, “Software reliability assessment based on the evaluation of operational experience”, *Measurement, Modeling, and Evaluation of Computing Systems and Dependability and Fault Tolerance*. Springer Berlin Heidelberg, 2010, pp. 24-38.

[3] R.N. Jazar, *Vehicle Dynamics: Theory and Application*, Springer Science and Business Media, 2008.

[4] L. Roman, A. Florea, I. I. Cofaru, “Software application for studying OPEL cars' reliability”, *ANNALS OF THE ORADEA UNIVERSITY. Fascicle of Management and Technological Engineering*, vol. 22, no. 1, 2013, pp. 313–316.

[5] C. Nagel, B. Evjen, J. Glynn, K. Watson, M. Skinner, *Professional C# 2012 and .NET 4.5*, John Wiley & Sons, Inc., 2012.

[6] B. Syverson, J. Murach, *Murach's SQL Server 2012 for Developers (Training & Reference)*, Mike Murach Associates Inc., 2012.

[7] P. Múčka, “Longitudinal Road Profile Spectrum Approximation by Split Straight Lines”, *Journal of Transportation Engineering*, vol. 138, no. 2, 2012, pp. 243–251.

[8] M. Agostinacchio, D. Ciampa, S. Olita, “The vibrations induced by surface irregularities in road pavements – a Matlab approach”, *European Transport Research Review*, Ed. Springer Berlin Heidelberg, December 2013.