SZENT ISTVÁN
UNIVERSITY
GÖDÖLLŐ

MECHANICAL ENGINEERING PHD SCHOOL

A COMPARATIVE ANALYSIS OF OFF-ROAD AND TEST TRACK STRESSES ON TOWED VEHICLES

Thesis of PhD work

László Gurmai

Gödöllő, Hungary
2015

Name of doctoral school:	Mechanical Engineering PhD School
Branch:	Agricultural Engineering
Head of doctoral school:	Prof. István Farkas, DSc Szent István University Gödöllő, Hungary
Supervisor:	Prof. Péter Kiss, PhD Institute of Process Engineering Faculty of Mechanical Engineering Szent István University Gödöllő, Hungary

…………………………………	…………………………………
Approval by head of school	Approval by supervisor

TABLE OF CONTENTS

NOTATION

a:	acceleration of single point on trailer	[m/s^2]
a_{max}:	maximum acceleration of single point on trailer	[m/s^2]
c:	spring rate	[N/m]
c_{fh}:	constant of the homologous equation for the half cylinder case	[-]
c_{zsz}:	constant of homologous equation for the box section case	[-]
d:	damping constant	[Ns/m]
f:	frequency	[Hz]
g:	acceleration of gravity	[m/s^2]
G:	load per wheel	[N]
$G_x(f)$:	power density function of terrain profile	[m^{2}s]
$G_y(f)$:	power density function of excited oscillatory system	[m^{2}s]
h:	height of box section	[m]
l:	track width	[m]
l_1:	distance between centre of mass and centreline of right wheel	[m]
l_2:	distance between centre of mass and centreline of right wheel	[m]
m:	weight	[kg]
n:	wavenumber	[1/m]
r:	radius of semi-cylindrical obstacle	[m]
R:	static radius of tyre	[m]
t:	time	[s]
T_G:	area under the power spectral density curve	[mm^2]
v:	towing speed	[m/s]
x:	displacement	[m]
y:	vertical displacement of the mass centre	[m]
y_1:	vertical displacement of the right wheel	[m]
y_2:	vertical displacement of the left wheel	[m]
y_3:	vertical displacement of the towing eye	[m]

ε:	exponent of homologous equation	[-]
Λ:	logarithmic decrement	[-]
σ:	standard deviation	[-]

1. INTRODUCTION, OBJECTIVES

1.1. Importance of the subject

High levels of reliability, cost-efficient production, design optimized to function, weight reduction, and designing components for a specified lifetime are a few of the demands which manufacturers have to meet on the vehicles they develop. The market is increasingly calling for design perfection and reliability of cars, trucks and agricultural machinery. Manufacturers need a large amount of information in order to design vehicle structures that meet these demands. This includes information on the dynamic stresses generated in vehicles when traversing uneven roads.

After the design stage, product development continues with functional testing, strength testing and validation of the prototype. This is the phase in which the designers determine whether the structure they are developing is satisfactory.

The design of off-road vehicles requires knowledge of the excitations deriving from the profile of the terrain they travel on. The faults generated in fatigue tests of off-road vehicles often differ from those which arise in real field conditions. This is because existing test methods do not model forces acting on vehicles under real conditions, or not with sufficient accuracy. The stresses generated in vehicles towed across terrain must be determined by series of measurements carried out in situ. The terrain models produced from these measurements may then form the basis for methods of fatigue testing that better approach the forces acting in reality, thus permitting improved design.

The motion of off-road vehicles, including trailers, is an area of separate theory and research. Research into the soil-tyre interaction has been in progress in the Szent István University for several decades. The book Terepen mozgó járművek (Vehicles Moving Across Terrain, Laib 2002), reviews the results of this research. My research took the results of previous work in the department as its starting point.

1.2. Objectives

The more extreme the conditions a vehicle is used in, the quicker it wears out. In order to determine the stresses that affect the lifetime of the vehicle, we have to discover the environmental phenomena that generate them. The objective of the research was to develop and test a method of comparing terrain characteristics and use it to devise fatigue tests that impose forces comparable to those which act on a vehicle moving across terrain.

Knowledge of the forces acting on towed vehicles in various terrain conditions will yield a procedure for fatigue tests by which the effects arising in normal operating conditions may be modelled. For the development of new towed vehicles, this will give a more precise picture, more quickly, of the likely failure points of the structure, contributing to more accurate and thus more cost-effective vehicle design.

The objective of the research is thus to analyse the relationships between vehicles and terrain of different conditions. This involves describing and testing the excitation forces acting on the towed vehicle as it interacts with the micro- and macro-obstacles of the terrain profile, and producing a method for comparing these effects.

A more precise specification of the objectives included the following requirements for developing the proposed comparative method:

- The method must compare road profiles without the need for a measuring vehicle, use only profile data, and be capable of implementation and evaluation anywhere.
- The method must give clear and classifiable results for the forces acting on vehicles traversing various road profiles.
- The results obtained using the comparative method must be applicable to the design of artificial road profiles for accelerated fatigue tests.
- The method must enable comparison of the stresses generated in vehicles by two different fatigue testing systems.
- The stresses generated in vehicles by the artificial road profiles designed using the new method must correspond to those caused by a road profile recorded under normal operating circumstances.

2. MATERIALS AND METHODS

As with agricultural vehicles, towed agricultural equipment is often required to perform their tasks in difficult terrain conditions. For the present research, we chose a towed structure which is characteristically used on agricultural dirt tracks. It is a trailer for transporting headers fitted to harvesting machinery for various crops.

2.1. Measurement methods

The general objectives of the research required measurement data to be gathered on the interaction between the vehicle and the ground. Separate measurements were required to record the profile of the artificial system of obstacles, and others to measure the stresses generated in the trailer and to determine the parameters of the trailer.

The first stage was to establish the dimensions, mass, centre of gravity, tyre spring characteristics, damping characteristics and natural frequency of the trailer used in the study. These parameters were then used to build the dynamic model of the vehicle.

The second stage was to measure the vibrational accelerations in the trailer set up by the excitation of the road profile at various towing forces. The excitation forces acting on the vehicle and the vibrations generated in it were recorded by measuring accelerations in three directions at several points on the trailer. These acceleration values permitted the determination of the amplitude and frequency of the excitations.

The third stage was to determine the terrain profiles. The road profile is the factor which most influences the vibration accelerations in the trailer. This implies that the excitation effect of the road profile is what causes most structural damage to the vehicle. Measurement consisted of recording the coordinates of profile points at constant distance intervals.

The main criterion for selecting a test trailer suitable for making series of measurements to be used in comparative analysis of terrain conditions was the ability to set up measurements simply and quickly. The SHERPA BG3 trailer (Figure 2.1), designed for transporting harvesting machinery headers, has a simple construction which is well suited to this purpose, being easy to model and having few potential failure modes.

Figure 2.1: SHERPA BG3 trailer and CONSPEED 8 row DUMMY header

Terrain effects were therefore measured on a single axle, semi suspended structure, i.e. the header trailer. The measurements taken for this research and conclusions drawn from processing the data obtained all concern this type of trailer.

The load carried by the trailer during the measurements was a purpose-built dummy header, shown on figure 2.2. In terms of its mass and centre of gravity, it is equivalent to an 8 row corn header. It was designed to allow the modelling of various load conditions by adding and removing auxiliary weights in the form of concrete blocks.

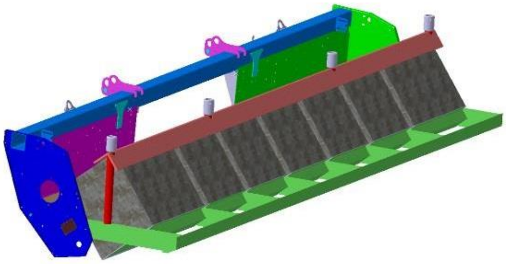

Figure 2.2: CONSPEED 8-75 C dummy header

Piezoelectric acceleration sensors to measure the dynamic response of the trailer were placed at the locations indicated in figure 2.3. The sensor outputs, corresponding to the vibrations of the trailer, were transmitted to a data collection unit.

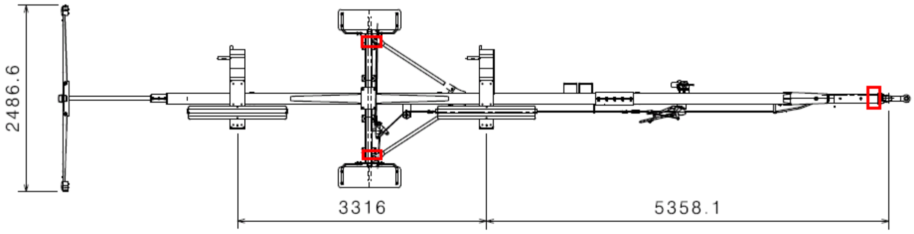

Figure 2.3: Acceleration measurement points on the single axle header trailer

Road profiles were recorded using a profilometer based on the communicating vessels principle, as shown in figure 2.4. During measurements, the profile was measured on both wheel tracks at 100 millimetre intervals along the predetermined route of the trailer.

Figure 2.4: Profilometer in operation on an asphalt surface

The measurement sequence had four distinct phases. The quantities measured in the first phase were the ability of the trailer to overcome terrain obstructions, the coordinates of its centre of gravity, and its vibrational characteristics.

The second phase consisted of measurements taken in realistic operational scenarios on roads of five different types. The first was a high-quality surfaced road, the second was a low-quality surfaced road, and the remainder were agricultural dirt tracks of three different soil types. Separate measurements were taken on sandy, clay-based and coarse gravel roads.

Figure 2.5: Section of asphalt road with broken surface and holes

The third phase of measurements consisted of a comparison of two accelerated fatigue testing systems. One system used a roller test bench (Figure 2.6) and the other a circular test track.

Figure 2.6: Measurements on roller test bench

In the fourth phase, I measured the effects of various artificial terrain obstacles and combinations of them.

Figure 2.7: Obstacle Calibration Measurement in Törökszentmiklós, at the site of CLAAS Hungaria Kft.

2.2. Analysis and evaluation of measurement results

Formulating the mechanical model of the transport trailer enabled us to determine the transmission characteristics of the structure. The structural design forming the basis of the mechanical model is shown on figure 2.8. The transmission characteristics are what determine the measurable responses of the system to road profile excitations. In the first approximation, we formulated a simplified mechanical model of the trailer and then determined the properties of each element of the model using measurement results.

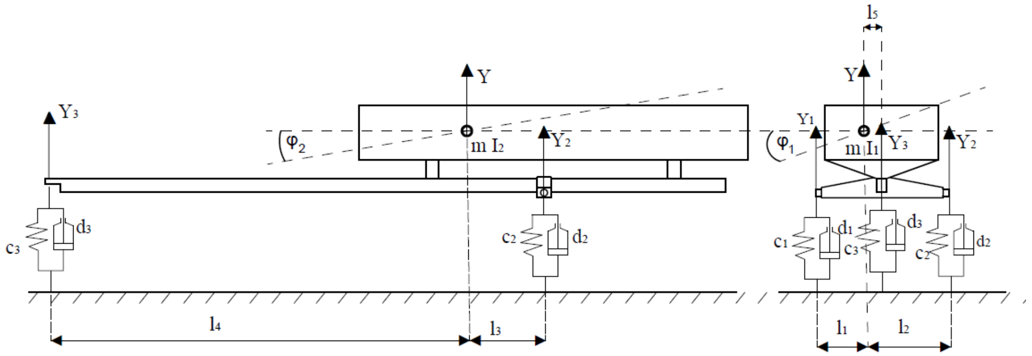

Figure 2.8: Vibrational model of trailer in front and side views

After formulating the analytic mechanical model, I produced the 3D model of the trailer as shown in figure 2.9. I then meshed the model and selected the links between elements for finite-element analysis of the whole structure. The meshed model of the trailer also formed the basis for modal and harmonic analysis.

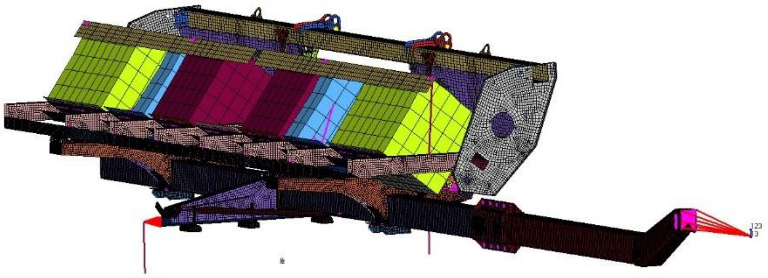

Figure 2.9: Mesh and constraints of the trailer model generated by the HyperMesh program

The analysis yielded the critical frequency ranges where the transmission characteristic was such that excitations caused high response function values. Figure 2.10 shows the vertical transfer function determined at three key points of the trailer. The graph shows that the transmission factor has a maximum value in the critical resonance range of the towed vehicle. Knowledge of the transfer function theoretically enables the response function of a given excitation spectrum to be calculated. The results of the simulation model and the field measurements, however, showed that knowledge of the excitation spectrum and the transfer function was not sufficient in itself for determination of the response function.

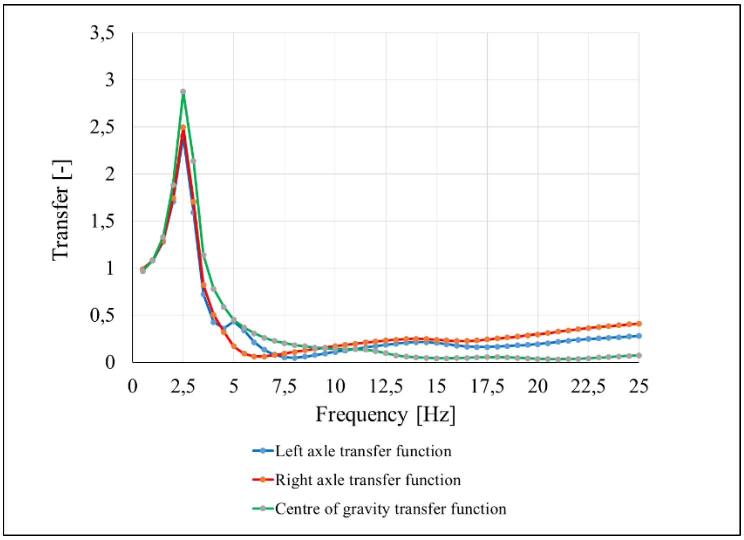

Figure 2.10: Vertical transfer functions determined at three points of the trailer

This shortcoming is attributable to the bouncing of the wheels. The excitation spectrum derived from the profile ceases to apply when the vehicle loses contact with the ground, thus altering the response function.

I then evaluated the series of measurements from the field towing tests. Using the terrain profile recordings, I determined the power density spectrum (PSD) for the surface, as shown on figure 2.11.

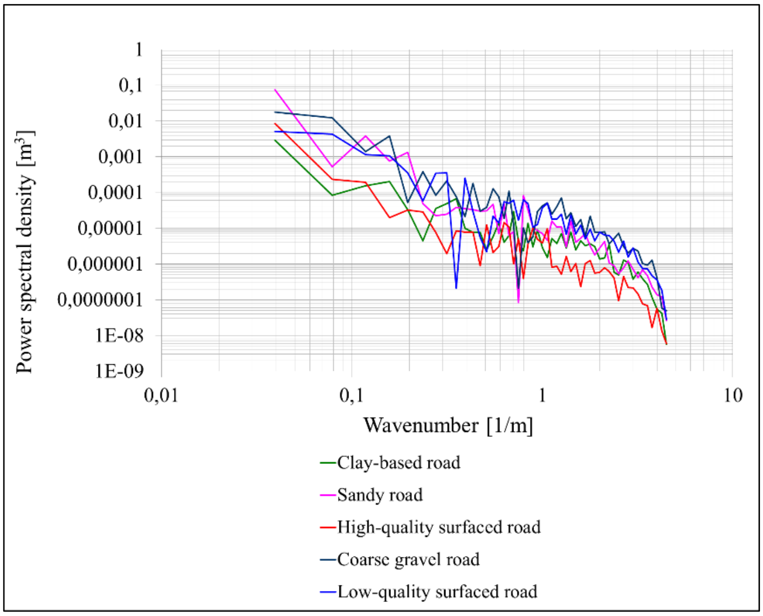

Figure 2.11: Power density spectra of terrain profile measurements

The graph shows that, as expected, the profile amplitude at most frequencies is lowest for the smooth, unbroken asphalt surface and highest for the coarse gravel surface.

The vibrational acceleration data recorded in the series of measurements on the trailer was then subject to analysis. First the extreme and root mean square (RMS) values were calculated, followed by the power spectral density (PSD). The PSD curves of the vibrational accelerations recorded on the coarse gravel road, shown on figure 2.12, are illustrative of the results. The curves show that tests on the same road profile at different towing speeds resulted in vibrational accelerations with different PSDs. The curves for different speeds are drawn in different colours and form each other's envelopes at steadily higher levels.

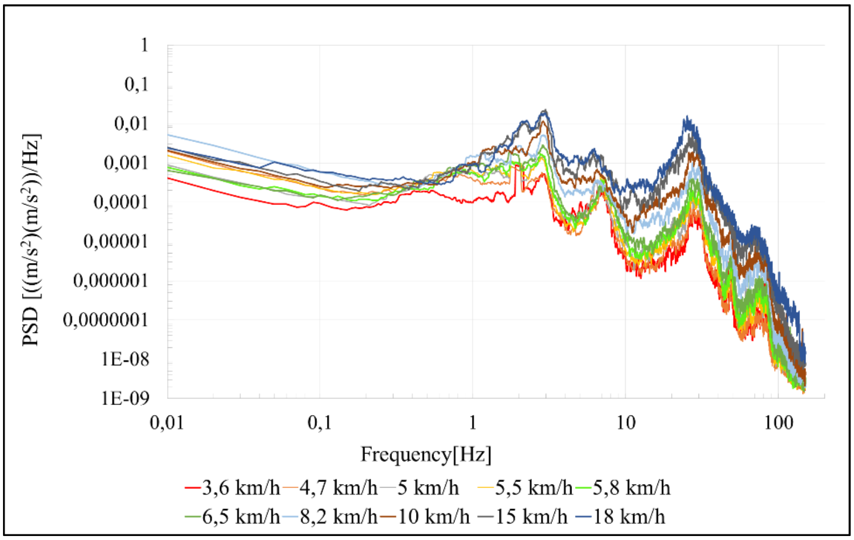

Figure 2.12: PSD analysis of the vertical vibrations on the left side of the trailer on a coarse gravel road at various towing speeds.

The local maxima of the PSD curves remain within approximately the same frequency range at different speeds. Regardless of the road profile type, the natural frequency of the structure was 2.5 Hz, with higher harmonics of between 5 and 30 Hz.

.

3. RESULTS

Here I discuss the results of the measurements concerning the relationship between the trailer and the different road profiles, in line with the objectives formulated in the introduction. I also discuss the comparative methods for evaluating how terrain profiles are related to artificial obstacle systems in terms of their effects on the vehicle.

3.1. Relationship between terrain profile and vehicle vibrations

Before commencing fatigue tests, it is necessary to determine, by a set of measurements, the maximum loads that occur under normal operation. This in turn requires the selection of load conditions which result in the appropriate range of stresses. For vehicles traversing roads of different stochastic characteristics, the magnitude of stresses is related to the excitation effect of the road profiles.

The nature of the profile can only be deduced indirectly from data gathered using a measurement vehicle. Different types of measurement vehicle yield different and incomparable results for the same stretch of road. It was therefore necessary to produce a comparative system which does not use a measurement vehicle and gives reliable and definitely comparable data on the excitations caused by road profiles. Put another way, we needed to devise a simply-applicable measurement method that could rank the magnitudes of stresses generated by different road profiles.

Stochastic terrain profiles are best characterized using PSD analysis. The PSD curve gives information on the relative amplitudes of a succession of obstacles, or more precisely on the spectrum of a series of obstacles.

My measurements led to the conclusion that the micro-obstacles (humps and holes) that occur on the types of roads used in agriculture, at low towing speeds, i.e. 20 km/h or less, are shorter than 2.5 metres, i.e. have wave numbers greater than 0.4 1/m. From the observed values, under the above criteria, the spectral range of the PSD curve for micro-obstacles is the range above the wavenumber 0.4 1/m. Accordingly, the study had to focus on amplitudes characterizing the heights of vibration-exciting obstacles within this range. Figure 3.1 shows the PSD of micro-obstacles on the road profiles measured in the course of field tests.

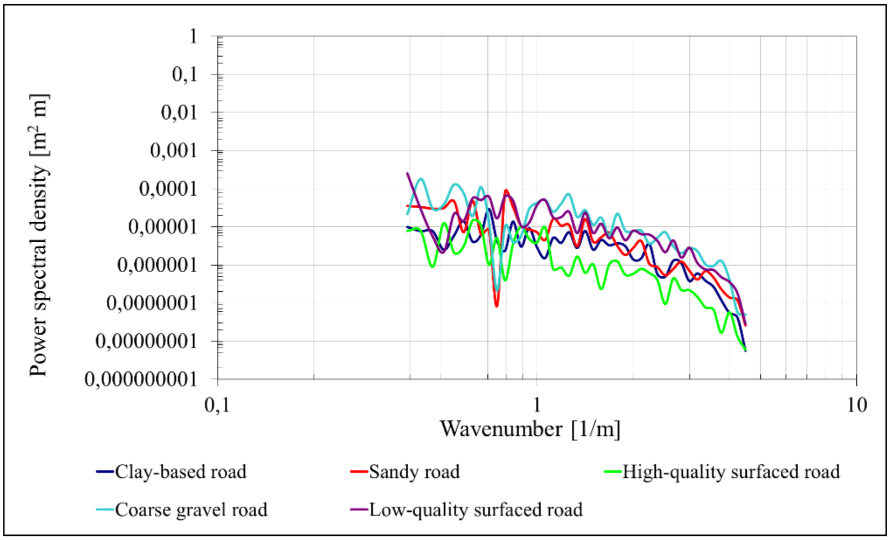

Figure 3.1: Left-side PSD curve of micro-obstacle systems of roads of various types

The curves do not permit the unambiguous ranking of amplitudes by magnitude, because several of them intersect. The ranking must be determined from the area under the curves. The area under the PSD curve (T_G) is given by the relation

$$T_G = \int_{0,4}^{\infty} G_x(\omega) d\omega \, , \tag{3.1}$$

where ω [1/m] is the wave number of the obstacles and G_x is the PSD of the road profile.

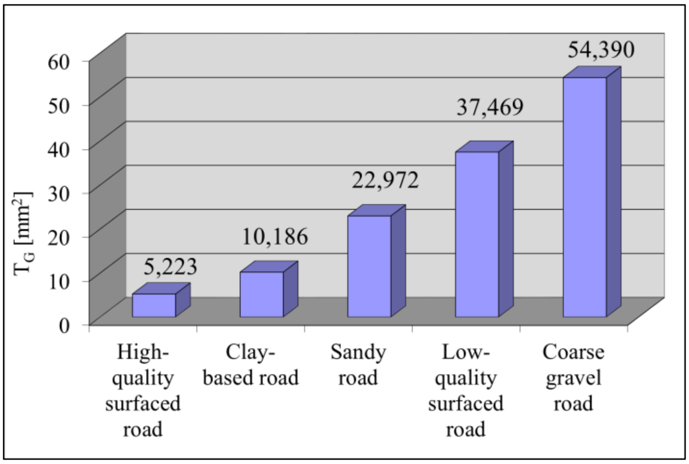

Figure 3.2: Areas under the PSD curves of micro obstacle systems of road types

This calculation yielded the data shown on figure 3.2, which clearly indicates the ranking of the areas under the PSD curves characteristic of the profiles. An important requirement for the area-based comparative method is that all of the profile recordings subjected to comparison are carried out over the same length and with the same measurement interval.

The area-based comparative method may be verified with the previously-used towing test. If the ranking of RMS values of the vibrational accelerations measured on the towed vehicle corresponds to the ranking of the areas under the PSD curves, then the evaluation method may be regarded as of general validity for the test trailer.

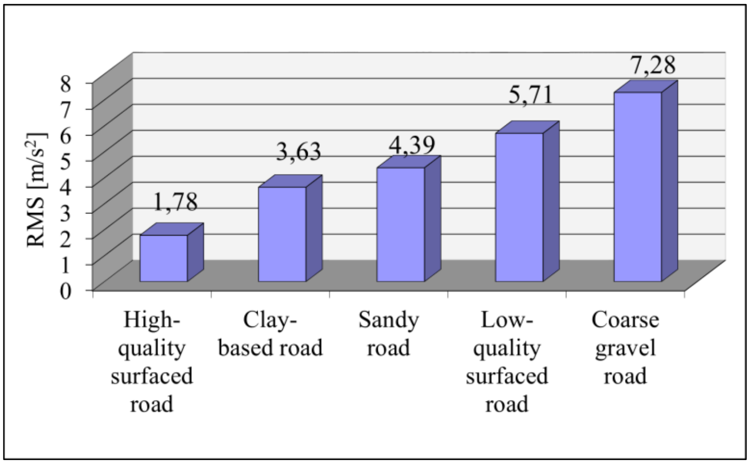

Figure 3.3: RMS values of vibrations caused by roads of various types at 10 km/h towing speed

Figure 3.3 clearly shows that we obtain the same ranking of roads of different profiles whether we use the RMS values of the vibrational accelerations measured on the vehicle or the areas under the PSD curves. This ordering of road profiles also shows up in the extreme values of the vibrational accelerations for the road profiles, i.e. the maximum positive and negative values. Figure 3.4 shows that the RMS values at various towing speeds also verify the road profile comparison methods based on the areas under the micro-obstacle PSD curves.

Overall, we have developed a road-profile-based comparative method which is capable of comparing various stochastic road profiles in terms of their action on the vehicle.

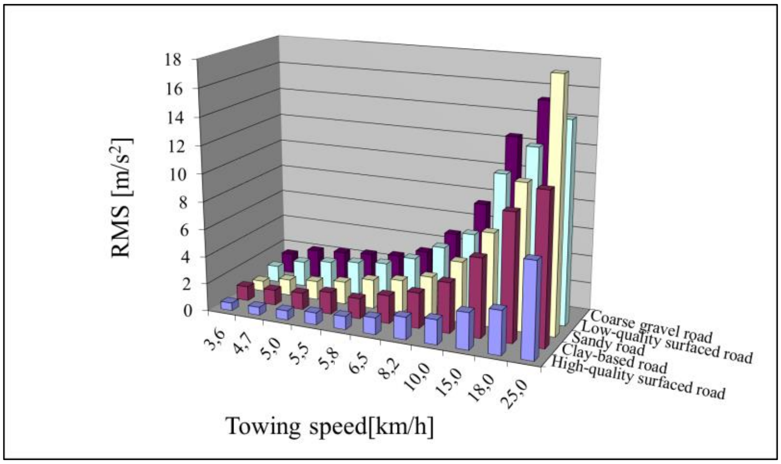

Figure 3.4: RMS values of the vibrations on the left side of the vehicle generated by various road types at different towing speeds

3.2. Distribution of vibrational acceleration

The RMS/a_{max} value tells us whether the series of recorded data is long enough and thus statistically acceptable, or is not representative. As the length of the data series increases, the RMS value converges to a characteristic figure and the maximum acceleration approaches the most extreme value of displacement for the road. If RMS/a_{max} for successive measurement series are approximately equal, then the measurements are statistically adequate. Figure 3.5 clearly shows that the standard deviation of accelerations at the same towing speed is higher for more uneven road surfaces, and that RMS/a_{max} lies between the values 0.2 and 0.3.

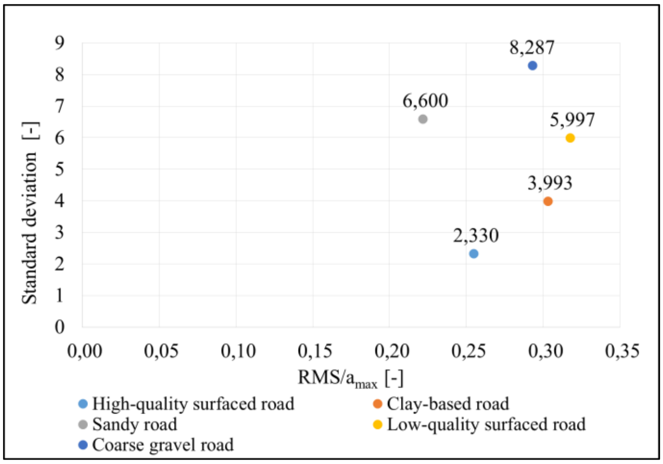

Figure 3.5: Standard deviation and RMS/a_{max} of vibrational accelerations in a vehicle towed at 10 km/h on various road types

For ideally normally-distributed systems, RMS/a_{max} has the value 0.18. In this case, the maximum acceleration (a_{max}) is the value at 3σ on the normal distribution fitted to the amplitudes and the RMS value is calculated from the means squares of the weighted amplitude at the corresponding points of the normal distribution. If the RMS/a_{max} of the accelerations measured on the trailer traversing the various road profiles differ from the ideal, then the distribution deviates from the normal distribution.

The deviation can be traced to the magnitude of the gradients between the points of the road profile. If there is a large deviation between the average and maximum obstacle heights, then we obtain a value of RMS/a_{max} lower than 0.18. Examples of such profiles are obstacle courses where the obstacles are considerably larger than the average profile height. If there is only a small difference between the average obstacle height and the maximum obstacle size, then we obtain a value of RMS/a_{max} smaller than 0.18. The stochastically-distributed profiles of agricultural roads are typically of this type. In these cases, there is a low average gradient between profile points, such as on a coarse gravel road, where the gravel has approximately constant height. If the distribution curve of the road profile amplitudes deviates from the normal distribution, then the values of vibration acceleration in a trailer traversing it will probably also deviate from the normal. This implies that the character of the road profile distribution may be established from the RMS/a_{max} values measured on the trailer.

3.3. Accelerations generated by impact of wheel and obstacle

Among the obstacle calibration measurements were towing tests performed on box section and half-cylinder obstacles at varying tyre pressures and towing speeds. The purpose of the measurement was to find the relation between the vibrational accelerations in a vehicle traversing the obstacles and the parameters influencing the phenomenon. The relations among parameters influencing the motion of the vehicle were determined using dimensionless numbers.

There are three identifiable stages in vibrational accelerations measured in the trailer as it traverses an obstacle. The first stage occurs in the moment of impact, when the wheel makes contact with the obstacle and then departs from it. In the second stage, the trailer is not in contact with either the ground or the obstacle, but is floating. In the third stage, when the wheel touches the ground, the maximum vibrational acceleration is measured. The vibrations set up in the structure subsequently attenuate. This process is shown in figure 3.6.

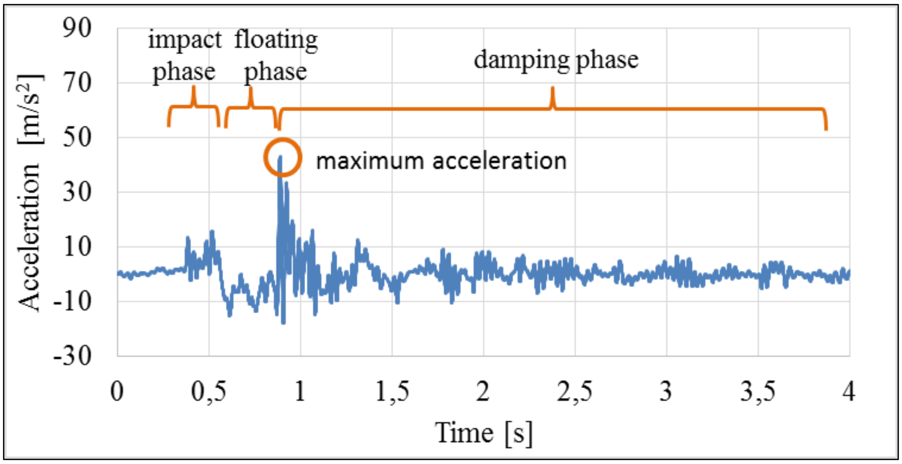

Figure 3.6: The three-stage interpretation of vibrational accelerations as the vehicle is towed over an obstacle, and the maximum acceleration (P=5 bar, v=5 km/h, box section 120 x 200)

Under the hypothesis, the vibrational acceleration generated by impact of the trailer with the obstacle is determined by the following parameters:

Tyre spring constant:	c	[N/m]
Static tyre radius:	R	[m]
Obstacle height (box section):	h	[m]
Obstacle height (half cylinder):	r	[m]
Trailer speed:	v	[m/s]
Trailer load on single wheel:	G	[N]
Acceleration of gravity:	g	[m/s^2]

Using the measured parameters and the method of formulating dimensionless numbers, I wrote a series of relations using the following dimensionless numbers describing the process in the impact stage:

$$M_1=\frac{a}{g},\qquad M_3=\frac{cv^2}{Gg},\qquad M_5=\frac{M_2}{M_4}=\frac{h}{R} \tag{3.2}$$

The homologous equation of these dimensionless numbers in the general form, expressed for the valueM_1, may be written

$$M_1=cM_5{}^{\varepsilon_5}M_3{}^{\varepsilon_3}\rightarrow\frac{a}{g}=c\left(\frac{h}{R}\right)^{\varepsilon_5}\left(\frac{cv^2}{Gg}\right)^{\varepsilon_3}. \tag{3.3}$$

The relation between the independent variables may be determined by substituting the values obtained by measurement.

The formula for the expected vibrational acceleration of the trailer as it crosses a box section is

$$a = g \cdot 1{,}004 \left(\frac{cv^2}{Gg}\right)^{0{,}5206} \left(\frac{h}{R}\right)^{0{,}6055} \tag{3.4}$$

and when the trailer crosses a half-cylinder obstacle, the formula is

$$a = g \cdot 0{,}8955 \left(\frac{cv^2}{Gg}\right)^{0{,}5206} \left(\frac{r}{R}\right)^{0{,}6055}. \tag{3.5}$$

Using these relations, it is possible to determine the expected vibrational acceleration without conducting a costly series of measurements.

I carried out vibrational acceleration measurements on towing tests on the circular track using obstacles of various sizes and types, at various towing speeds and tyre pressures. These results are given in Annex M21 of the thesis. The identifying numbers used there correspond with the numbers of the measurement results shown in the following figures. I compared these measured vibrational accelerations with the expected accelerations calculated using the equation to check the accuracy of the equation. The measured and calculated vibrational accelerations for the box sections are shown in figure 3.7.

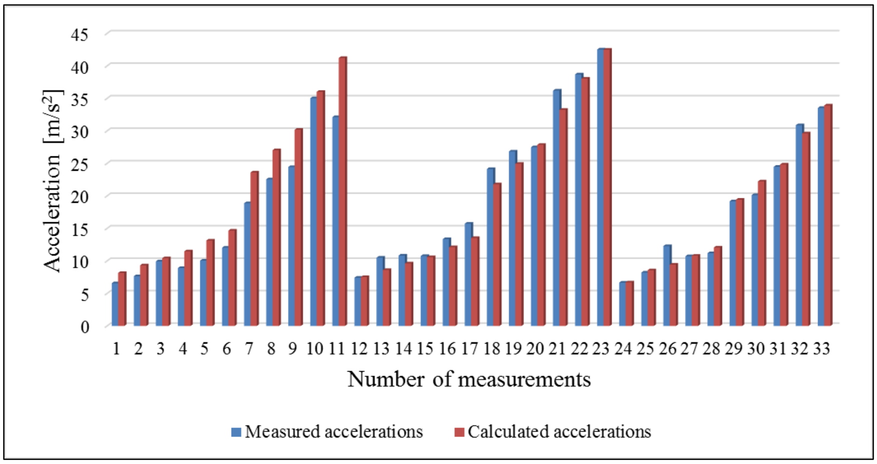

Figure 3.7: Comparison of measured and calculated vibrational accelerations of the trailer crossing box section obstacles

In this case, the average deviation between measured and calculated values in absolute terms was 10%. The comparison of measured and calculated vibrational accelerations for the half-cylinder obstacles had an average deviation of 9.4%. For the purposes of the test, both comparative equations are of satisfactory accuracy.

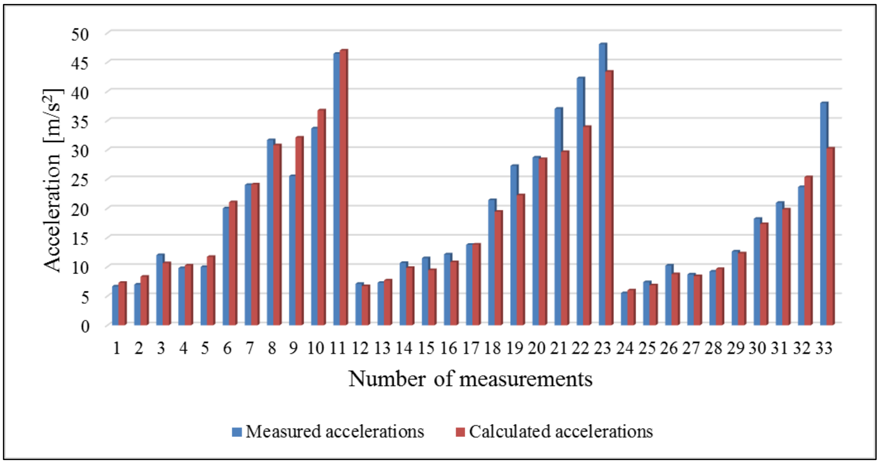

Figure 3.8: Comparison of measured and calculated vibrational accelerations of the trailer crossing half-cylinder obstacles

A further result is that half-cylinder obstacles of the same size, with the same set parameters, cause less vibrational acceleration than box section obstacles. The reason for this is that the gradient at which the trailer's centre of gravity is raised by the obstacle is lower for the half cylinder than for the box section.

3.4. Method of comparison of terrain profiles

The purpose of the test is to compare the profiles of different roads. The method compares the magnitude of the effects of terrain profile macro-obstacles acting on vehicles. The method, independent of the vibrational characteristics of the vehicle, identifies the road profile which causes the largest vibrational accelerations as the vehicle passes over it. The comparison procedure comprises the following steps:

1. The first step is to gather the terrain profile data. This consists of recording profile coordinates on a stretch of road at least 50 metres long at intervals of 100 millimetres or less along the routes used by the vehicles.
2. The second step is to determine the power spectral density of the recorded terrain profile.
3. The next step is to calculate the area under the PSD curve for the micro-obstacles. In accordance with the definition of micro-obstacles, the area under the curve is calculated for the range of wavenumbers greater than 0.4 [1/m].
4. Finally, the road profiles are ranked in order of the areas under their curves. The road which generates the greatest stresses in vehicles that traverse it is the one whose PSD curve encloses the largest area.

The method enables the stresses generated in vehicles by different sections of road to be compared without towing tests. It is important to note, however, that the method is not suitable for a comparative study of deterministic, i.e. artificially-created, cyclically-repeating, profiles.

3.5. Comparison of built obstacle systems

I developed a method for comparing and classifying the stresses generated by obstacle systems during fatigue tests. I found that the excitation frequency of obstacles had a negligible influence on the resonance range of the response function measured on the vehicle, but considerably altered the amplitudes of the response function. This result prompted the conclusion that in order to compare the stresses caused in the vehicles, it was necessary to study the amplitudes of the vibrations set up during the excitations. The data could then be used indirectly to characterize the density and size of the obstacle system. The comparative method involves determining the extreme and RMS values of the vibrational accelerations measured on the structure at each speed of travel. The stresses which the obstacle systems generate in the vehicles always depend on the structure, and so the measured values cannot be generalized. Nonetheless, the method has general applicability.

3.6. Design method for built obstacle system

In line with the objectives, the method of comparison of road profiles determines which of the arbitrarily-selected agricultural road profiles causes the greatest stresses in the vehicle. The comparative method is not, however, suitable for comparing the stresses caused by systems of discrete, cyclically repeating obstacles. Comparison of the area under power spectral density curves thus cannot form the basis for a comparison of artificially-constructed fatigue test methods. A different method must be used for this purpose.

Fatigue tests must be designed to create stresses equivalent to those experienced in real operating conditions. If the fatigue test stresses are too high, the structure will fail during the validation test, causing it to be strengthened further than is necessary and become excessively expensive. If the fatigue test stresses are smaller than normal operational stresses, then the vehicle may fail more quickly than expected.

In order to develop an appropriate artificial obstacle system, it is necessary to perform a comparative test of stresses in the structure under artificial and realistic conditions. With that provision, extreme vibrations caused by excitations near the natural frequencies can be avoided. Selection of an obstacle system suitable for fatigue tests must involve the following steps:

1. Select the most critical road type that can occur in normal operating conditions, using the comparative method for agricultural roads.

2. Determine the stress collective. Perform the towing test at the highest acceptable speed under normal operating conditions. This involves measuring the vertical accelerations of the vehicle axles beside the tyres as it traverses the road section.
3. Determine the extreme and RMS values of the accelerations for each towing speed.
4. Calibrate the obstacle system. Set up an obstacle system suitable for the fatigue test so that it generates the accelerations obtained in the field measurements. The objective is to set up an obstacle system which reproduces with an accuracy adequate for the procedure the RMS and extreme values of the vibrational accelerations measured on the road. The setup requires selection of the layout, dimensions and shape of the obstacles and selection of the appropriate towing speed. The system consists of cycles of successive obstacles of equal shape and layout. We must first select the obstacle type that causes the maximum vibratory excitation in the cycle, and then obstacles generating smaller vibrations. The iterative steps of composing the test cycle is completed when the vibrational accelerations measured during the towing tests are equivalent to the desired maximum and RMS values.

The stress collective generated in the vehicle structure by the resulting fatigue testing system is similar to that which occurs under normal operating conditions. To conduct the fatigue test, however, it is also necessary to define a quantity which represents what the structure must withstand in order to meet the manufacturer’s requirements. This quantity must be proportional to energy input, and may be the duration of the test or the number of impacts. It must be determined in a way that relates to the methods of calculating lifetime. Validation of the vehicle thus involves defining firstly the relevant stress collective and secondly a test cycle which is related to the required lifetime.

3.7. Practical results of the research

1. Benefits of comparability of terrain profiles

The method of comparing the systems of micro-obstacles in stochastic road profiles ranks the profiles in terms of the stresses they generate in the vehicle. In practice, this could be used to classify the road network of a specific area in terms of possible damage to vehicles travelling across it. Thus knowledge of road profiles could enable the selection of the route that causes least damage to vehicles. This could have great significance in cases where it is important to be able to travel through an area quickly and safely. Using the method could greatly facilitate the selection of safe routes for (forestry and military) vehicles to move through agricultural and other terrains.

2. Generally applicable fatigue testing method for off-road vehicles

I have developed a method for determining a generally applicable stress collective for the fatigue testing of trailers travelling over terrain. This method allows the reproduction of forces which arise in normal operating circumstances and the generation of damage equivalent to the faults that occur in such circumstances. The aim of the method is to model real stresses in any type of fatigue test. This means that the method could be used with any test system capable of generating the corresponding excitations. In each case, the system of obstacles used in the fatigue test must correspond to the operational load levels. If the responses (vibrational accelerations) have been measured as prescribed and the load levels set accordingly, then the test can be reproduced using any fatigue testing method. A fatigue test set up in this way could thus be suitable for vehicle validation purposes.

3. Applicability of fatigue testing system to other types of machinery

The fatigue testing method developed here is applicable to any vehicle exposed to the stresses generated by difficult terrain. Since it produces terrain profiles which depend on real operational stresses, the method can be applied generally to various vehicle structures. These may include towed and self-propelled agricultural and forestry equipment.

4. Comparison of previously-applied fatigue testing methods

The method for comparing the stresses generated by built obstacle systems may also be used to compare the stress collectives of existing fatigue testing systems. This could rank standardized fatigue testing systems in order of the stresses they generate, and thus determine the extent to which the test system under- or overloads the test vehicle compared to normal operational loads.

5. Optimizing vehicle construction

Knowledge of the excitation frequency of stochastic road profiles enables field vehicles to be designed more precisely. Knowledge of the excitation frequency and amplitude allows the damping of oscillations in the vehicle structure to be adjusted to obtain the required lifetime. This contributes to the attainment of optimal design of field vehicles (appropriate damping elements, vehicle mass, geometry, centre of gravity, etc.).

Fatigue test systems based on the method of terrain simulation developed in this project could find applications in optimizing vehicle construction. More specifically, it would be possible to avoid over- or underscaling with fatigue tests that employ the appropriate load collective. As a result, instead of the usual standardized load, the load levels to which the test structure is optimized would reflect real working conditions.

4. NEW SCIENTIFIC RESULTS

In accordance with my objectives, I examined the effects on towed vehicles of roads with artificial profiles and roads with stochastically-distributed profiles. The results I obtained may be grouped into seven areas.

1. I have justified that different stochastic road profiles cause equivalent damage to the vehicle structure if the power spectral density curves of their micro-obstacle profiles enclose equal areas. The area under the curve obtained from the spectral analysis of the micro-obstacles (T_G) is given by the equation

   $$T_G = \int_{0,4}^{\infty} G_x(\omega)d\omega$$

   where ω [1/m] is the wavenumber of the obstacles and G_x is a function of the power density of the specific road profile. The comparative method validated by the extreme values of vibration and *RMS* values measured in towing tests of a specific trailer at different towing speeds.
2. I have determined that it is possible to rank stochastic road profiles in terms of the damage they cause to towed vehicles. The ranking is based on the area under the curve (T_G) obtained from the spectral analysis of micro-obstacles on the road. This yields a generally applicable comparative method for comparing and grading damage effects on single-axle towed vehicles using no more than the recorded road profiles.
3. The measurement results verify that the profile excitation function at most only slightly affects the characteristic frequency range of the vehicle response. For a trailer in the category examined, it is not possible to derive the road profile responsible for the excitations from the characteristic amplitude-frequency curve of the vehicle vibrations. In other words, measurements on a towed test vehicle permit no general conclusions about the excitation effect of the road profile.
4. I have proved that different road profiles have the same damaging effect on the vehicle structure if both the extreme and RMS values of the vibrations they generate in the structure are equal. This statement has general validity for any two road sections of equal length, whether they have stochastic or deterministic profiles.
5. The value of RMS/a_{max} for the vibrations measured in a vehicle towed along a road profile indicates how closely the statistical distribution of the vibrations fits the normal distribution. The closer it is to the figure 0.18, the closer the fit. Values of RMS/a_{max} lower than this occur when the road

profile contains a low frequency of the obstacles that cause transient effects, and vice versa.

6. I have contrived a relationship for determining the vibrations caused by collision of the wheel with an obstacle. The parameters affecting the relationship are towing speed, spring stiffness of the tyre, static wheel radius, obstacle size, weight of towed vehicle per wheel and acceleration due to gravity. The vibration brought about at the moment of impact with a box section obstacle is described by

$$\mathrm{a} = g \cdot 1{,}004 \left(\frac{cv^2}{Gg}\right)^{0{,}5206} \left(\frac{h}{R}\right)^{0{,}6055}.$$

The equivalent relation for a half-cylinder obstacle is

$$\mathrm{a} = g \cdot 0{,}8955 \left(\frac{cv^2}{Gg}\right)^{0{,}5206} \left(\frac{r}{R}\right)^{0{,}6055}.$$

5. CONCLUSIONS AND SUGGESTIONS

This chapter presents the some suggestions which have arisen from the research and may be elaborated and developed to be a useful continuation of its practical and theoretical work.

Since the research drew on several branches of science and engineering (soil science, off-road theory, lifetime calculations, vehicle dynamics), the suggestions and ideas for future developments touch on several different areas of research.

A review of the literature led to the conclusion that the comparative method I have used, based on RMS and extreme values, may be applicable as a system for the evaluation of cumulative damage. The method may also be suitable for comparative analysis of vibrational accelerations in a vehicle traversing a road section of specified length. I suggest that it would be useful to determine values I measured using the method of accumulated damage and to compare the results.

A new aim of research is to determine a damping ratio for the level of compaction of different soil types. The energy absorbed in deformation of the soil, i.e. the soil’s vibration damping effect greatly reduces vibrations in the vehicle. I propose that another area of research could be a study of the speed of the tyre’s depression into the soil from the point of view of soil deformation.

When using the ADAMS simulation program in my research, I found that the model of the pneumatic tyre greatly influenced the effectiveness of the virtual measurements produced by the program. The behaviour of a real tyre with adjustable parameters equivalent to those used in the model deviated considerably from the behaviour of the virtual tyre. Since the reason for this deviation is unknown, further research is required to develop better tyre models for towed structures used in agriculture.

Structural failure involves absorption of energy. To improve the comparability of fatigue testing, it would be useful to select a parameter which is proportional to the energy input. The method of determining the energy per wheel during the fatigue test provides a means of defining the energy to be input to each wheel over the full validation cycle. This would permit determination the energy used and remaining to be used during the fatigue test for any obstacle system and towing speed. The method would thus allow comparable validation of vehicles with different dynamic characteristics whatever test system is used. I propose that developing this method would be an important step forward for the validation of vehicles.

6. SUMMARY

The lifespan of a vehicle is significantly influenced by the forces acting on it during operation. The more extreme conditions the vehicle is exposed to, faster it wears and deteriorates. In order to determine the forces affecting the lifespan of vehicles we need to know the environmental conditions eliciting these forces. This research aimed to elaborate and test a method of comparative analysis of the forces acting on vehicles under different terrain conditions.

Fatigue tests on terrain vehicles have often generated different malfunctions from those which occur in real terrain conditions. This suggests that the testing methods do not model the forces acting on vehicles under real conditions with sufficient accuracy. In order to identify the damaging forces acting on vehicles towed over terrain, there was a need for a generally-applicable comparative method capable of designing a fatigue test that models real conditions more accurately.

The first step was to determine the mechanical properties of the soil and the effects of terrain profile on vehicle motion. The second step was to determine the mechanical and mechanical vibrational properties of the observed vehicle, so as to obtain the transfer function of the structure. A series of measurements was then performed to determine the stresses caused by various stochastic and built obstacle systems. These stresses in the structure are described by the response function under excitation. The fourth step was to develop a comparative test method to determine the excitations generated by various road profiles.

The many series of measurements conducted during my research have yielded results that are applicable in both the theory of off-road vehicles and the validation of vehicles. I have developed a general method for comparing stochastic road profiles based on the destructive effects which their micro obstacles exert on vehicles. In addition, I have worked out a method for comparing the excitations generated in vehicles by built terrain obstacle systems, and a scheme for vehicle fatigue tests. The methods I have developed offer a basis for designing more reliable fatigue test systems which correspond to the loads experienced under normal operating conditions. The use of fatigue tests based on the new method should reduce the problem of under- or over-dimensioning of off-road vehicles due to improper validation procedures.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Refereed papers in foreign languages:

1. **Gurmai, L.** – Kiss, P. (2014): The Towed Vehicle as an Oscillating System. International Journal of Heavy Vehicle Systems Vol. 21, No. 3, 2014, pp. 262-280. ISSN: 1744-232X
2. **Gurmai, L.** – Kiss, P. (2014): Analysis of relations of towed vehicles and road profile. Journal of Tekirdag Agricultural Faculty, volume 11/1, pp. 90-97. ISSN: 1302-7050.
3. **Gurmai, L.** (2010): A comparative study of methods used for testing towed vehicles. Hungarian Agricultural Engineering N°22/2009 pp. 46-48. HU ISSN 0864-7410
4. **Gurmai, L.** – Kiss P. – Laib L. (2012): Modelling of Terrain and towed vehicle interaction. Mechanical Engineering Letters, volume 6, pp. 88-92. ISBN: HU ISSN 2060 - 3789
5. **Gurmai, L.** – Kiss P. – (2012): Comparative analysis of destructive forces acting on the structure of off-road towed vehicles. Mechanical Engineering Letters, volume 8, pp. 98-106. ISBN: HU ISSN 2060-3789

Refereed papers in Hungarian:

6. **Gurmai, L.** (2013): Terepen vontatott jármű fárasztóvizsgálatainak összehasonlító elemzése [Comparative analysis of fatigue tests on vehicle towed on terrain]. Mezőgazdasági Technika. LIV. évfolyam, 2-5. o. HU ISSN 0026 1890
7. **Gurmai, L.** (2012): Terepviszonyok hatása a mezőgazdaságban alkalmazott vontatmányokra [Effect of terrain conditions on agricultural trailers]. Mezőgazdasági Technika. LIII. évfolyam, 19-21. o. HU ISSN 0026 1890
8. **Gurmai, L.** (2011): Szállítókocsik tesztelése és validációja a terepviszonyok figyelembevételével [Incorporating terrain conditions into the testing and validation of transport trailers]. Járművek és Mobil Gépek online folyóirat (http://on-and-off-road-vehicles.hu) , III. évf., 1. sz., No.I. 49-58. o. HU ISSN 2060-4408
9. **Gurmai, L.** (2013): Vágóasztal-szállító kocsi fejlesztése [Development of a header transport trailer]. Járművek és Mobil Gépek online folyóirat (http://on-and-off-road-vehicles.hu), 1-8. o. HU ISSN 2060-4408