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Zbyszko KLOCKIEWICZ*
Grzegorz ŚLASKI*

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ANALYSIS OF VEHICLE'S SUSPENSION'S DYNAMIC RESPONSES DURING TEST TRACK RIDES AND REAL EXPLOITATION

The following paper presents a study of dynamic responses of a passenger vehicle in typical exploitation conditions. It describes the process of acquiring data from the test rides and their further analysis using statistical values using MatLab. The analysis focuses on accelerations of sprung and unsprung mass, suspension deflection and its speed, comparing the values achieved on different road surfaces, taking into account safety limits and suspension characteristic. The data acquired are presented as graphs of density of probability and cumulative empirical probability, as well as tables listing dynamic responses undergoing analysis. The results allow for estimation of expected dynamic responses of a vehicle, thus making the preparation of future experiments more thorough.

Keywords: suspension, dynamic responses, kinematic excitations.

1. INTRODUCTION

Vehicle's suspension system serves an important role, being the link between the road surface and the vehicle's chassis. In normal exploitation the most important forces acting between the vehicle and its surrounding are transferred by the suspension's parts. In vertical direction these forces can either be of static nature, i.e. the static load from the vehicle weight, or dynamic like the forces present during vehicle movement [Liu and Huston, 2011]. In relation to these two types of loads needs to serve dual purpose as well. First of all, it should distribute static loads possibly evenly between all wheels of the vehicle, as well as minimize the changes to this distribution when the vehicle moves on different surfaces. Secondly, it should also minimize the dynamic loads exerted on the body when the vehicle

* Poznan University of Technology.

is in motion. For these reason the vehicle's suspension systems are built as dynamic structures in which the kinematic excitations are changed into dynamic ones, which allows to reduce the forces affecting the vehicle's chassis [Mitschke, 1977]. Suspension system in functional sense converts the inputs into outputs, which are defined as any chosen variables describing dynamics of sprung and unsprung mass and their combinations. The inputs can be either force or kinematic excitations. Force excitations are forces that act on the vehicle from the outside. These include aerodynamic forces when the vehicle moves, forces from acceleration and deceleration of a vehicle, lateral forces from the wind or in extreme cases sudden impacts of objects falling on the vehicle. Kinematic excitations are the road excitations defined by changes of road height profile, vehicle's velocity and filtering properties of a tire. Kinematic excitations usually play a bigger role during vehicle's motion and this paper deals with suspension responses to them, treating force excitations as negligible.

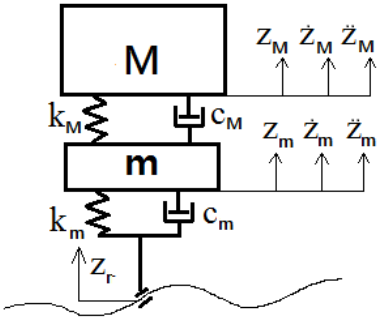

Fig. 1. Quarter-car model of a suspension with kinematic excitation (zr) and dynamic responses (zm etc., zM etc.) [Jazar 2008]

Kinematic excitations can be further divided into determined obstacles, periodical irregularities and random irregularities. The first group includes all the obstacles, that have a finite geometry which can be defined, for example a train track, a pothole in the road or a curb. Such obstacles usually appear sporadically and not in easy to predict intervals, that is why they are analyzed in time-domain. Such obstacles, even though they make up only a small portion of the vehicle's exploitation time, are important as many extreme accelerations and deflections of a suspension occur when they are encountered. Periodical irregularities are rarely seen in real exploitation, as they are the most artificial in nature and can usually be described using mathematical functions like sine [Liu and Huston, 2011]. The example of real irregularity close to periodical could be a road made out of regular paving stone. Harmonic excitations' usefulness comes in the form of being a good testing bed for dynamic properties of a suspension system. The last category – random irregularities – includes almost every real road, because of their innate irregular and random character.

The outputs from the suspension system are, as mentioned before, the dynamic responses. Dynamic responses are defined as every quantity that is a result of processing of inputs to the system, as well as the correlations between such quantities. From the number of responses the most important are the ones which define variables important from the functional or construction point of view. The first group includes quantities such as accelerations of a sprung mass that affect ride comfort and vertical forces between tires and road surface that contribute to traction and thus to ride safety [Liu and Huston 2011,Siłka 2002]. From the construction point of view crucial dynamic responses are suspension deflection, that define the working range of suspension, as well as the speed of deflection that is responsible for a sizeable part of the forces acting between suspension elements [Prochowski 2005].

The knowledge how the car reacts to different excitations is very useful when designing a suspension system, that is why test tracks are built to examine how the suspension works in known conditions. These test tracks however do not cause the same dynamic responses as real road exploitation. Furthermore, the existing literature rarely describes real road in the context of dynamic responses [Jazar 2008, Dukkipati et al. 2008]. Instead most publications focus on determined obstacles or periodical irregularities, which are much easier to describe than more or less random real road profile functions. In connection with those facts the question that arose was what are the real road exploitation dynamic responses of the passenger car and how do they compare between different types of roads, as well as with the responses registered during test track rides.

Considering how important the knowledge about the values of dynamic responses in various road conditions is, the research goal was established to compare their values when driving over different surfaces with varying speed, that were meant to represent typical driving conditions encountered in real life exploitation. Based on that dynamic responses' characteristics of typical road profiles, like highway, city road or cobblestone road could be made and later used to test, whether it is possible to calculate from the measurable dynamic responses the ones, that can't be measured directly, like the forces in the suspension. To do all that, proper methods of measurement and analysis needed to be developed and tested.

2. METHODS OF RESEARCH AND RESULT'S ANALYSIS

The research on this topic included two phases – experimental and analytical ones. The experimental phase required the testing vehicle to be fitted with sensors and data recording devices followed by the executions of test rides on the real roads as well as on the test track. The second phase consisted of filtering and sorting out the data from the experiments, after which statistical calculations and working on the results' representation in the graphical form took place.

The vehicle used during testing was Opel Astra III Estate passenger car. It was chosen to represent a popular group of segment C (compact) passenger vehicles, with similar dynamic properties to models like Volkswagen Golf or Renault Megané. The car was equipped with adjustable dampers, that were set in 3 different settings – comfort, normal and sport. On the car there were accelerometers fitted on all the wheels near their axis, measuring unsprung mass acceleration, as well as over each separate wheel measuring sprung mass acceleration. Additional acceleration sensor was mounted in the center of mass of a car, recording accelerations in all 3 directions. Each wheel's suspension deflection was registered using distance sensor. In order to get the suspension deflection's velocity it was calculated by differentiating measured suspension deflection values.

The vehicle during tests carried 2 passengers – a driver and a person running the data acquiring process. Another significant weight added onto the vehicle was a pack of batteries from a heavy-duty vehicle that powered independently the computer and sensors attached to it. The batteries were mounted in the trunk of the vehicle, weighing down the rear axle. The approximate weight of both passengers were 80 kg, the batteries weighed about 40 kg, while the mass of the vehicle itself was 1400 kg.

The test rides consisted of two parts – first one conducted on real roads in Poznań and second one that took place on the test track. The exploitation part of experiments took place on a few selected streets in and around Poznań. The roads were chosen based on their surface and speed limit. 4 types of a road were selected:

- highway section, with speed limit of 140 km/h
- high quality city road, speed limit of 80 km/h
- bad quality asphalt road, speed limit 50 km/h
- cobblestone road, speed limit of 50 km/h.

Test track surfaces were made to mimic the toughest kinematic excitations encountered in real-life exploitation. Three surfaces on the test track analyzed in this paper were different types of cobblestone roads, similar to those encountered in exploitation. These surfaces spanned for about 50 m each, which allowed for some measurements to be made, however it must be clarified that such a short distance might not produce all the dynamic responses, for example those associated with macroprofile of the road. Every surface was driven over multiple times, registering dynamic responses of a vehicle each time. Test track rides consisted of three consecutive rides with velocity of 30 km/h (as the test track manual suggested) and fourth ride with 10% higher speed. All these test were made with 3 different damping settings – high, normal and low. Similar tests were carried out in real exploitation, however the speed had to be adjusted to match the traffic conditions at the time of data acquisition. Moreover not all damping settings were tested in real exploitation, as the time needed for those tests was limited.

The results were gathered and registered by the computer carried inside the vehicle. For the processing MatLab script was written, which algorithm for can be divided into following steps:

- data loading,
- defining start and stop times of the ride on the tested surface,

– matching the responses matrixes’ items with corresponding time matrix items,
– dividing the results into classes based on ranges of empirical probability,
– calculating density of probability and cumulative empirical probability of different responses,
– drawing graphs of analyzed quantities.

After loading experiments’ results, the second step’s goal was to divide test results into fragments of close to constant velocity, to minimize the impact of a change of vehicle’s speed on the dynamic responses. This created both new time matrix, as well as all the dynamic responses’ new matrixes, corresponding to one another. Then these results were divided based on their value – for example the accelerations were grouped into those of the range from 0 m/s^2 to 1 m/s^2, then from 1 m/s^2 to 2 m/s^2 and so on. The number of elements of each class was calculated and based on that number the density of probability as well as cumulative empirical probability were calculated. Lastly statistical values like mean value, standard deviation value, maximums and minimums were calculated.

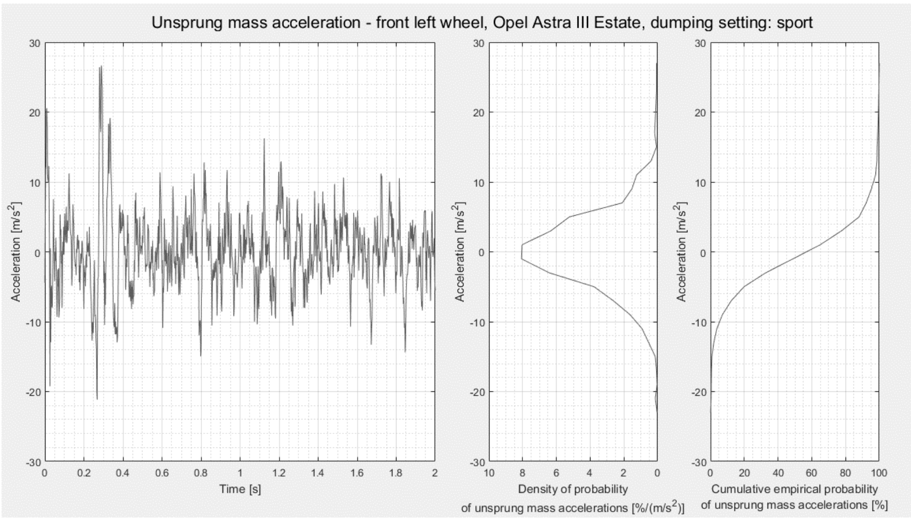

Fig. 2. Example of a plot showing unsprung mass acceleration of a front left wheel

The results of previously described processing were organized in graphs for easier interpretation. Fig.2 shows how the basic time series and density of probability and cumulative empirical probability charts correspond to one another. Those graphs, as well as time series of measured dynamic responses were drawn to be later used in the analysis.

To compare different surfaces in quantitative way tables with statistical data were created, with extreme values as well as mean and standard deviation values of dynamic responses on different roads and with different damping settings.

3. RESULTS ANALYSIS

In this chapter the following dynamic responses of a car will be described: accelerations of unsprung mass, accelerations of sprung mass, suspension deflection and suspension deflection's velocity; in that order. The influence of road surface and damping setting on aforementioned dynamic responses will be the topic of this chapter.

Accelerations of unsprung mass: As can be seen in fig. 3, the recorded accelerations of unsprung mass achieved the highest values for cobblestone road, which was to be expected. The results for highway and ordinary asphalt road are quite similar to one another, however the bigger share of accelerations for

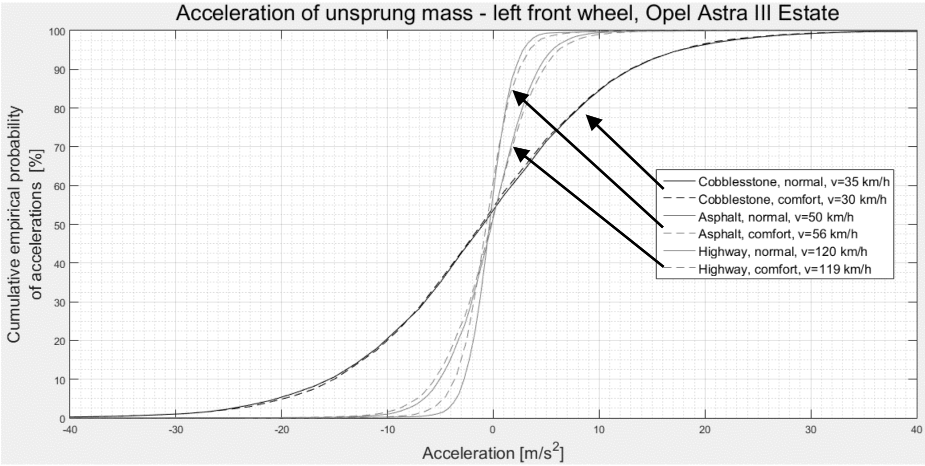

Fig. 3. Comparison between unsprung mass accelerations with normal and comfort damping setting on different roads

highway have higher values. Values between +/– 10 m/s^{2}are not exceeded by 98% of highway accelerations, while for the asphalt road the same can be said for 99.8% of accelerations. This might be caused by the lower speed limit on that road combined with the fact, that the road in question was of quite good quality. On the cobblestone road accelerations from the range of +/– 10 m/s^2 make up only 60% of all recorded results, so the forces generated on such surface are undoubtedly bigger.When it comes to comparing the accelerations of unsprung mass in connection with the damping setting, the biggest difference is observed on the normal asphalt road and the highway – the accelerations increase in value in the comfort setting, for instance the range of +/– 10 m/s^2 includes 98% of all accelerations for normal setting, but only 96% for comfort setting. Similar change can be observed for the asphalt road. On the other hand, the change for the cobblestone road is almost nonexistent, lowering the accelerations of unsprung mass by at most 0.5%.

Another information that might be useful in future research when choosing the right accelerometer for the job are extreme values, which can be found in table 1. For both asphalt and highway they are bigger than +/– 50 m/s^2, with the negative values being greater in absolute value. The only exception to this is asphalt with comfort setting, this however might be because by pure chance there wasn't any pothole or similar obstacle that would cause a big acceleration.

Table 1. Statistical values for unsprung mass accelerations

Accelerations of unsprung mass	Highway			Asphalt			Cobblestone		
	normal		comfort	normal		comfort	normal		comfort
	100%	90%	100%	100%	90%	100%	100%	90%	100%
Maximum value [m/s^2]	49.4	5.4	50.4	51.5	3.1	30.1	51.5	17.4	51.3
Minimum value [m/s^2]	–67.7	–6.5	–41.7	–72.7	–3.9	–23.6	–72.7	–20.5	–72.7
Standard deviation value [m/s^2]	4.04		4.33	2.99		2.61	11.8		11.5

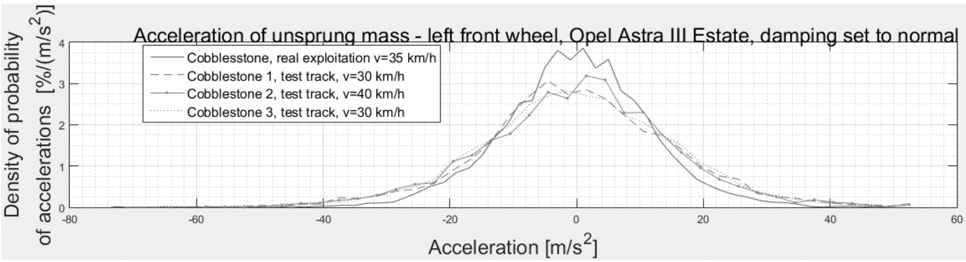

Fig. 4. Comparison between cobblestone test track and real road unsprung mass accelerations, normal damping setting

This is also the reason why extreme values are not suitable for in-depth analysis and drawing general conclusions – they are rarely encountered and roads of vastly different quality could have similar extreme values, even though the ride comfort on one of them is vastly superior to the other – as is the case with asphalt and cobblestone in this comparison, having the same maximum and minimum values, while in reality they are clearly different surfaces. The best tool for such comparison is standard deviation, that confirms previous observation, that the accelerations on asphalt road have the narrowest range and in general smaller values – with standard deviation value of 2.99 m/s^2 compared with 4.04 m/s^2 for highway and almost 4 times greater value of 11.80 m/s^2 for cobblestone. The comfort setting in general slightly reduced the standard deviation values, the change however was never bigger than 0.3 m/s^2.

Next step was to compare the unsprung mass accelerations between real road and test track surface. Because the only test track surfaces that could be directly compared to the actual roads were the cobblestone segments of the test track, they are the ones subject to analysis in this part. As can be seen in the graph, the accelerations of unsprung mass are quite similar on all 3 testing segments and the real road, with close to one another maximum and minimum values. The density of probability for acceleration value of 0 m/s^2 was 3.8 %/(m/s^2) for real road and slightly lower for the test track, ranging from 3.6 to 2.8 %/(m/s^2).

Accelerations of sprung mass: while acceleration values for sprung mass are much lower than those of unsprung mass, their distribution is similar. The highest values, exceeding +/– 30 m/s^2 were registered when driving on cobblestone road, while highway and normal asphalt did not exceed +/– 10 m/s^2. The only exception to that is a single registered acceleration on normal asphalt that reached 34 m/s^2, this however can be attributed to random obstacle and is not typical for such a surface.

Table 2. Statistical values for unsprung mass accelerations

Accelerations of sprung mass	Highway			Asphalt			Cobblestone		
	normal		comfort	normal		comfort	normal		comfort
	100%	90%		100%	90%		100%	90%	
Maximum value [m/s^2]	8.4	2.1	7.1	23.9	0.9	4.1	23.8	6.4	19.6
Minimum value [m/s^2]	–9	–3.1	–7.4	–9.5	–2.3	–9.2	–32	–5.1	–31.2
Standard deviation value [m/s^2]	1.54		1.57	1.03		0.96	4.89		4.15

On cobblestone road 90% of sprung mass accelerations belong to the range of +7/–9 m/s^2, while on the asphalt the range is +1/–2 m/s^2 and for the highway +2.5/–3 m/s^2, while the damping is set to normal. The results imply that it is more comfortable to travel on the normal asphalt road than on a highway – however one must take into consideration much higher speed, with which the car goes, as the difference between these 2 surfaces is not that noticeable for passengers. For comfort the most important are accelerations greater than 1 g, i.e. greater than around 10 m/s^2. Such accelerations are not present when driving on asphalt roads, however they can appear on the cobblestone – as can be read from the graph, only around 95% of all recorded accelerations have value lower than +/– 10 m/s^2. Comparing different damping setting it can be concluded that this time the biggest difference can be seen on cobblestone road, with comfort setting successfully lowering sprung mass accelerations – now only 2% of all accelerations exceed +/– 10 m/s^2. There is almost no difference when it comes to damping setting and sprung mass acceleration on asphalt road or highway.

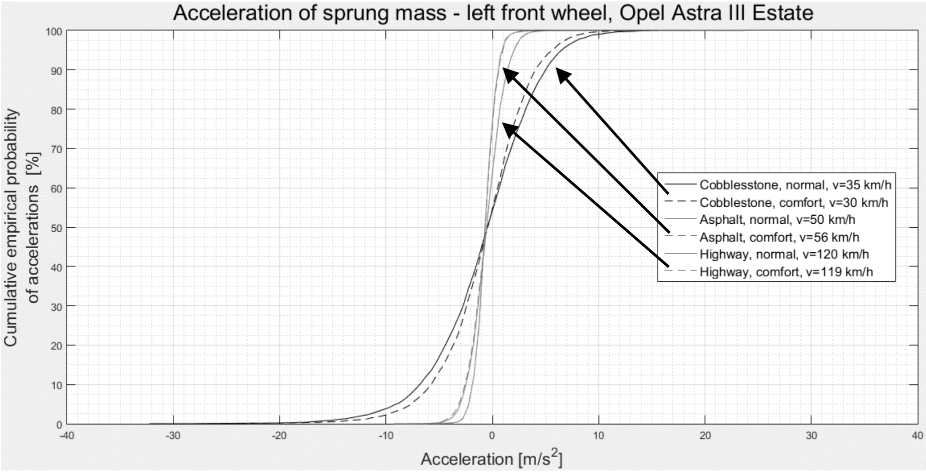

Fig. 5. Comparison between sprung mass accelerations with normal and comfort damping setting on different roads

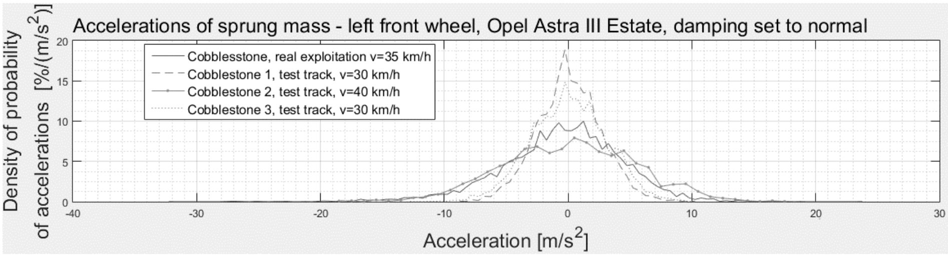

Fig. 6. Comparison between cobblestone test track and real road sprung mass accelerations

Sprung mass accelerations for both test track and real road cobblestone were once again pretty similar to each other, even more so than unsprung mass accelerations. Real road had slightly higher extreme values (+25/–30 m/s^2 compared to around +20/–15 m/s^2) and density of probability for 0 m/s^2 being 9.5 %/(m/s^2) instead of around 9%/(m/s^2). Such a disparity in results is relatively small, meaning that test track cobblestone simulates real road accelerations of both sprung and unsprung mass quite well.

Suspension deflection: The fig. 7 shows another important dynamic response that was compared between different road types. The deflections on asphalt road and highway are almost identical to one another, at least when normal damping setting is in place. Standing out once again is cobblestone road, with much bigger spread of values – 90% of all results for highway and asphalt are in the range of +0.005/–0.007 m, while the same percentage for cobblestone includes the range of +0.016/–0.019 m.

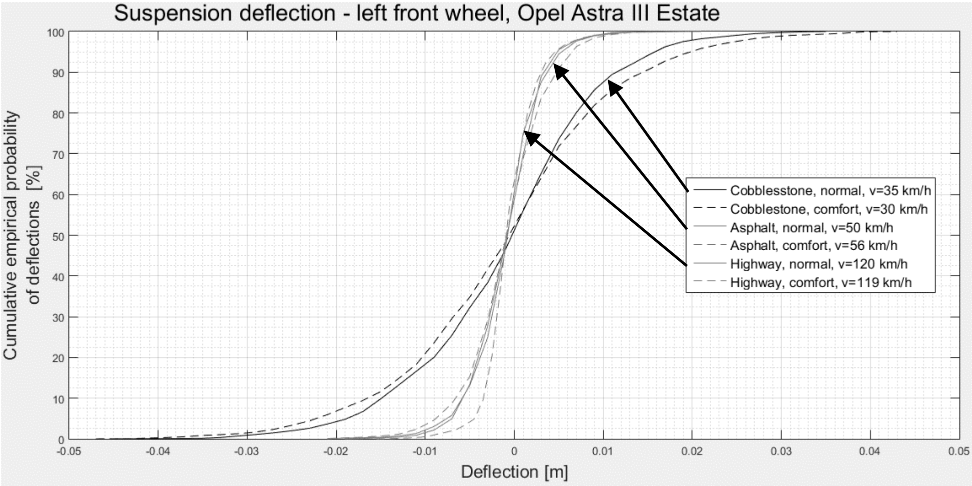

Fig. 7. Comparison between suspension deflections with normal and comfort damping setting on different roads

Those values become even greater when comfort damping setting is activated – the range for asphalt changes to +0.007/–0.009 m and for cobblestone to +0.020/–0.023 m. On the highway however, the opposite can be seen – the values decrease to +0.005/–0.005 m, which suggests that the damping coefficient changes with the vehicle's speed – when traveling at higher speeds, to achieve better comfort stronger damping can be beneficial.

Table 3. Statistical data for suspension deflections

Suspension deflections	Highway			Asphalt			Cobblestone		
	normal		comfort	normal		comfort	normal		comfort
	100%	90%		100%	90%		100%	90%	
Maximum value [m]	0.021	0.005	0.021	0.019	0.005	0.018	0.036	0.016	0.043
Minimum value [m]	-0.019	-0.008	-0.016	-0.022	-0.008	-0.021	-0.045	-0.019	-0.046
Standard deviation value [m]	0.004		0.003	0.004		0.005	0.011		0.012

Extreme values for asphalt road and highway were quite similar to one another, with slightly higher values for the latter. This is probably caused by the higher speed that the vehicle achieves on the highway, as was speculated earlier. The standard deviation and mean values for these surfaces are also similar, at least with normal damping setting. Changing it to comfort causes standard deviation to decrease for the highway and increase for the asphalt road. The cobblestone is characterised by much bigger extreme values – about twice as big as on either asphalt or highway. The standard deviation is also much larger, being 2.5 higher compared to the rest. With different road surfaces being different from one another, these values can be used in adaptive control system to determine what kind of surface the car is driving on [Dąbrowski and Ślaski, 2016].

The deflections registered in the experiments were then used to plot them onto the spring characteristic of the testing car. Spring characteristics were acquired in the testing procedure described in [8]. The characteristic is shown in the upper graph of fig. 8 as a thick line and can be described as typical for car suspension spring, with the linear relation between force and deflection in the middle part and non-linear at the edges. When deflection reaches a certain point (0.125 m in this case) the bump stop starts to work, increasing the force needed to compress the spring further. Onto that characteristic the spring deflections from the experiments were plotted, thus showing how much of the whole work range of the spring was used.

The vertical lines in fig.8 represent suspension deflections that correspond to 10% and 90% of cumulative empirical probability of occurring of such deflection. That means that 80% of all recorded deflections on a given road are located between the lines of colour corresponding to density of probability chart of that road type.

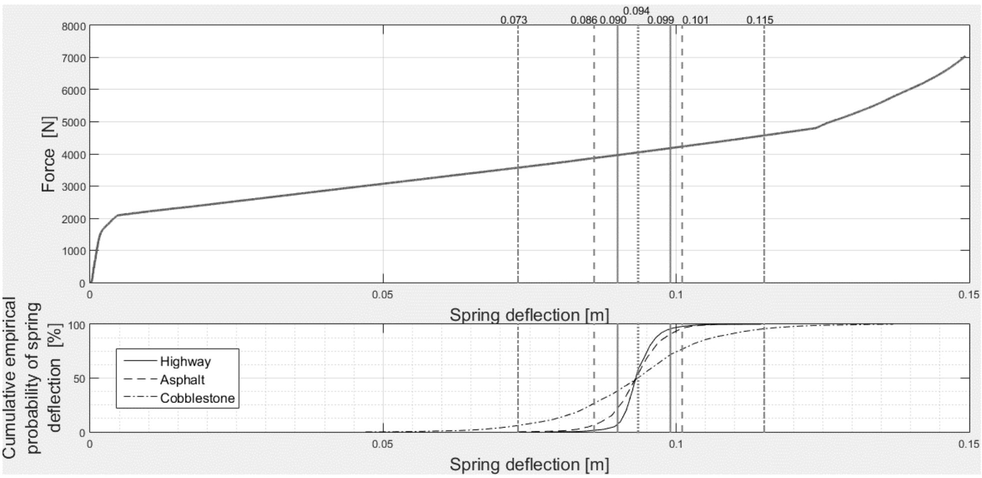

Fig. 8. Spring deflections on different surfaces against spring characteristic – 10% and 90% values. Thick line represents spring characteristic [Ślaski and Pikosz, 2010]

In normal exploitation all the oscillations of the suspension should be contained within linear part of spring characteristic. In the case of the vehicle used in experiments, this linear part is 0.115 m long, however it is not symmetrical – static load deflection is closer to upper limit, in which the bump stop starts to act. 90% of all deflections on highway use up only $\frac{0.009}{0.115} \cdot 100\% = 7.8\%$ of the whole available spring deflection range. For the cobblestone this percentage is higher and is equal to $\frac{0.42}{0.115} \cdot 100\% = 36.5\%$, but still less than a half of a working range of the suspension is used. At the same time, some of the responses exceeded the linear range of suspension work while driving on cobblestone – even if the percentage of those responses was minimal, under 1%.

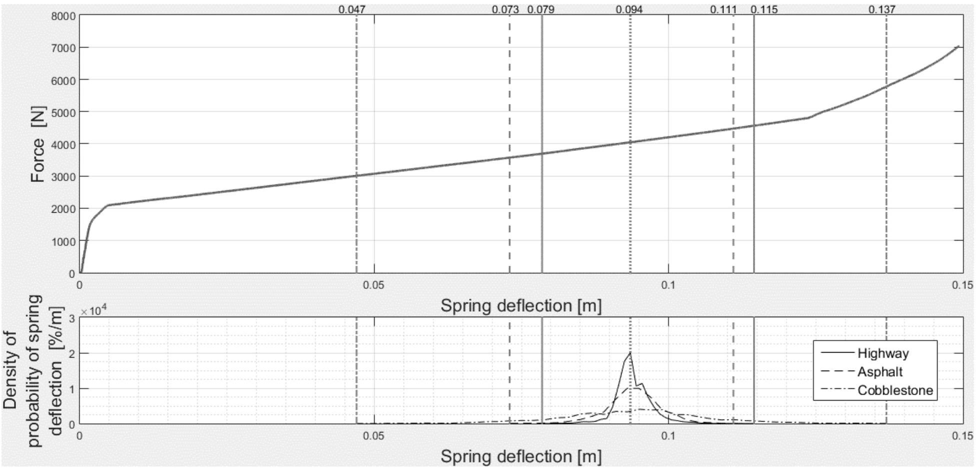

Fig. 9. Spring deflections on different road types plotted against spring characteristics (represented by a thick line [Ślaski and Pikosz, 2010])

Deflections on real cobblestone road were also compared to those on the test track and while accelerations of both sprung and unsprung mass were similar to those achieved in exploitation. However, when considering other dynamic responses (fig. 6) such as suspension deflection the similarity is not that visible, with real road ride having a lot broader range of deflections, that sometimes reached +/- 0.030 m, while on the test track the extremums reached half of this value – 0.015 m. Similarly, for a deflection of 0 m real exploitation had a density of probability value of 5000 %/m, while the test track surfaces had double that value, exceeding slightly 10000 %/m. Such a difference can in part be attributed to higher speed in real exploitation, but more important is probably the not really random surface that covers the test track – it is designed to simulate only a narrow range of deflections, which as it turns out is not enough to recreate real life faithfully.

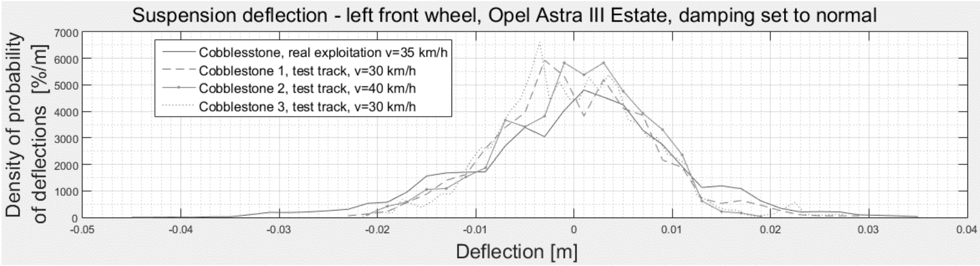

Fig. 10. Comparison between cobblestone test track and real road deflections

Suspension deflection's speed: as was previously mentioned, the suspension deflection speed was the only dynamic response analysed here that was not measured directly, instead it was calculated from the recorded deflection by differentiation. As such, those results are subject to the biggest value uncertainty. The graphs themselves are similar to those of suspension deflection. The values for cobblestone road were once again much higher than on the asphalt road or highway. What is interesting, the damping setting had very little effect on calculated deflection velocities, much smaller than on the deflections themselves.

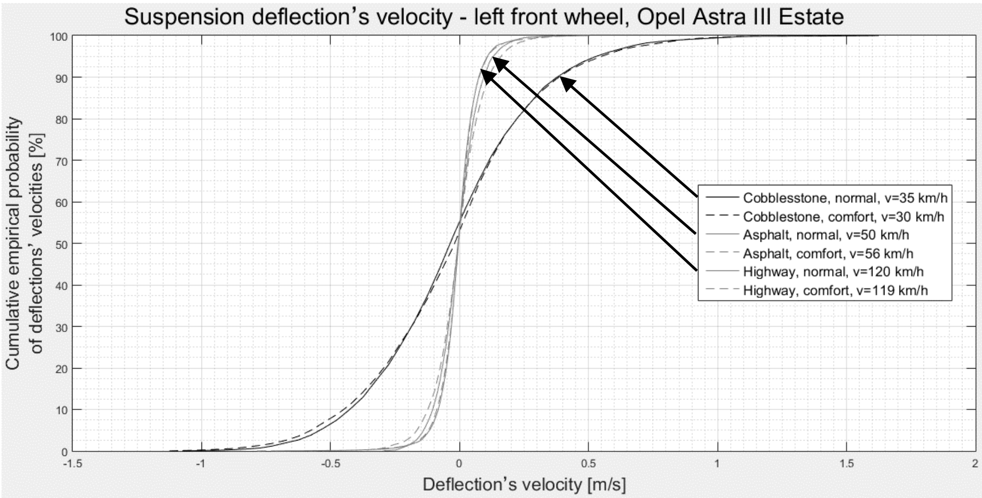

Fig. 11. Spring deflections' velocities on different road types

Similarly to deflections the maximum and minimum velocities of real road are almost double the value of those on the test track. This once again proves, that test track surfaces cannot fully mimic the effects of driving over a cobblestone road, as not all the responses of a suspension system are comparable.

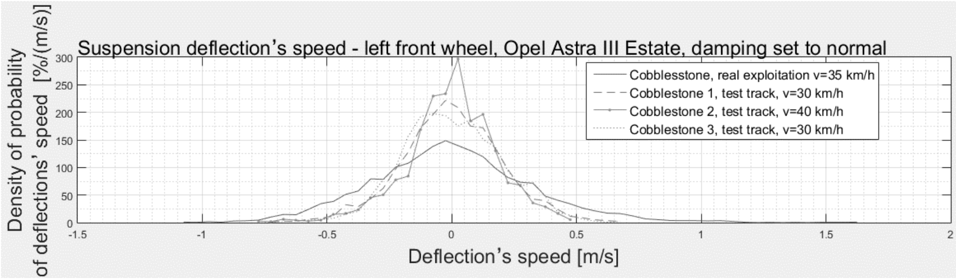

Fig. 12. Comparison between cobblestone test track and real road deflections

Table 4. Statistical data for suspension deflections and its speed

Suspension deflection's velocity	Highway			Asphalt			Cobblestone		
	normal		comfort	normal		comfort	normal		comfort
	100%	90%		100%	90%		100%	90%	
Maximum value [m/s]	0.51	0.12	0.49	0.38	0.13	0.48	1.65	0.52	1.64
Minimum value [m/s]	–0.71	–0.13	–0.78	–0.30	–0.14	–0.59	–1.1	–0.55	–1.11
Standard deviation value [m/s]	0.08		0.08	0.08		0.10	0.33		0.34

4. CONCLUSIONS

Experiment's results brought the researchers to many conclusion concerning the testing methods and possible future improvements that can be made to those methods. Firstly it was established, that statistical analysis will be the right tool for this research, as random nature of the road profiles that were driven on in the experiments necessitated long measurements with numerous measuring points. This in turn meant that there was a lot of data to be processed, for which statistical analysis is very efficient.

The test rides confirmed expected differences between examined surfaces when using different damping settings, implying that used measurement methods were correct and can be used in the future research, while at the same time shedding some on light on the principles of the algorithm, that regulates the damping. The prediction was that using softer damping setting will make more of the recorded unsprung mass accelerations closer to 0 m/s^2 and the experiment proved that to be the case. At the same time it was observed that suspension deflections do not always increase when the setting is changed from normal to comfort – when the vehicle's speed is high enough, the algorithm might harden the suspension, so it doesn't react to the smallest irregularities of the road profile.

Having established the right tools for results' processing and confirmed the measurements accuracy other comparisons could be interpreted. Test track surfaces do not fully mimic real road excitations. The reason might be their „designed randomness" instead of real random character. The fact that they visually are similar does not mean that dynamic responses of a car suspension will be the same. Test track is well suited for simulating accelerations of sprung and unsprung mass, however broader spectrum of irregularities is necessary to mimic ones encountered in exploitation

Test drives in real exploitation allowed to estimate the values of different dynamic responses that can be expected when driving on certain types of roads. This in turn will help to plan future, more detailed and specific experiments. Even though the results presented in this paper can be treated as preliminary to the main research activity in the future, they allowed to draw conclusions concerning real-life working spectrum of a suspension system by comparing suspension characteristics with recorded deflection. By juxtaposing these, it can be read which portion of a suspension's spring working range is used to what degree on different surfaces. Such information can be crucially important for someone designing a new suspension system, as it will give them better understanding of real life working conditions of different elements as well as help them determine the conditions for testing against fatigue for example. These results show also how often the bump stop starts to act and what are the effects of its activation. It might be also possible in the future to find ways to directly calculate the stresses that are transferred to the chassis by suspension elements based on the measured or simulated dynamic responses, which once again would greatly improve the possibilities of designing suspension systems. The tables 1 to 4 allow can help authors as well as other researchers to estimate what measuring ranges the sensors in the experiment should possess, while also being useful for comparing different road surfaces.

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ANALIZA ODPOWIEDZI DYNAMICZNYCH ZAWIESZENIA POJAZDU PODCZAS JAZD NA TORZE TESTOWYM I RZECZYWISTEJ EKSPLOATACJI

Streszczenie

Niniejszy artykuł opisuje badania odpowiedzi dynamicznych zawieszenia samochodu osobowego w typowych warunkach eksploatacyjnych. Zaprezentowano w nim sposób pozyskania danych z jazd testowych i ich dalszej analizy statystycznej w programie MatLab. Analiza skupia się na przyspieszeniach masy resorowanej i nieresorowanej, ugięciu zawieszenia i jego prędkości, porównując wartości otrzymane na różnych typach nawierzchni z uwzględnieniem typowych ograniczeń prędkości na danym typie drogi i charakterystykę zawieszenia. Zebrane dane ukazane są w formie wykresów gęstości prawdopodobieństwa i skumulowanej częstości oraz tabel opisujących analizowane odpowiedzi dynamiczne. Wyniki pozwalają na określenie przybliżonych wartości odpowiedzi dynamicznych, tym samym ułatwiając przygotowanie przyszłych badań.

Słowa kluczowe: zawieszenie, odpowiedzi dynamiczne, wymuszenia kinematyczne