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ANALYSIS OF VEHICLE VIBRATIONS – NEW APPROACH TO RATING PAVEMENT CONDITION OF URBAN ROADS

ABSTRACT

Urban road infrastructure is daily burdened by heavy traffic volume. Pavement structure roughness observations are significantly more difficult in urban agglomerations than on roads in unpopulated areas. Roughness, expressed by IRI (International Roughness Index), directly affects the quality and safety of road traffic. Within the framework of the pavement management in relation to safety and the achievement of the best possible ride comfort, it is very important to foresee when a road should be reconstructed. The method for quality evaluations of safety and ride comfort on urban roads presented in this paper is based on vehicle vibrations measurements. In the article, measuring of vehicle vibrations was performed on the main urban roads in Zagreb (Croatia). Measurements covered roads with different pavement surface roughness. This method can be simply and very easily used in pavement management aimed at achieving road safety and better ride comfort. The results of measurements according to this method could be used by traffic and civil engineering experts as an indication for the roads that require reconstruction or maintenance.

KEY WORDS

urban roads, traffic flow, safety, vehicle vibrations, road surface roughness (IRI)

1. INTRODUCTION

In addition to its basic function to provide sufficient load-bearing capacity for vehicles, pavement structure also has to provide safety and driving comfort. Various pavement imperfections not only reduce safety and driver and passenger comfort but they also damage of vehicles [1]. The movement of vehicles along an uneven pavement causes not only the vibrations in vehicle itself and for its passengers, but those vibrations are also transferred to structures (most often residential and commercial buildings) that are situated near heavily burdened roads, [2, 3].

The article investigates to what level the road surface in urban areas affects the vehicle vibrations and, consequently, passenger safety and ride comfort. Relating pavement surface condition with vibration intensity transferred to the vehicle gives an opportunity to traffic and civil engineers to evaluate the pavement condition and to systematically and rationally plan road maintenance and reconstructions.

According to the Law on public roads [4] and the Regulations on public road protection and maintenance [5] road and objects survey and usability is run by recognized Authority for roads [5]. Decisions on need of maintenance are made upon scheduled road surveys. Methods and criteria for grading the pavement usability (roughness) are well known [6] and are generally used on road in unpopulated areas, but very rarely in urban areas. Methods, if applied, are used for determining roughness in scope of pavement evaluation after renewal or reconstruction [7], rarely for evaluation prior to the reconstruction.

The parameter for the roughness evaluation of the paved traffic surface, i.e. the measure of the driving comfort, is the International Roughness Index (IRI), which is scaled in units of metre/kilometre (m/km). This parameter describes a vehicle's reaction to uneven spots in the pavement, which is most appropriate for the analysis of pavement evenness for driving comfort, dynamic loads, determining recommended vehicle speeds, and the overall condition of the road, [8]. To reduce the vibrations and increase level of safety and driving comfort, regular maintenance of roads, road-rail intersections and track pavements, in some cases complete reconstruction is required. In this article several cases of car vibrations have been considered in the investigation:

- on urban roads with poor pavement structure and large traffic volume (before and after reconstruction), Zagreb Avenue, Case A;
- on rail-road intersections; Šubićeva-Zvonimirova intersection (direction: South-North); Držićeva-Vukovarska intersection (direction: South-North); Savska-Vukovarska intersection (direction: East-West); Case B;
- on urban roads with tram tracks incorporated in their composition (tram tracks are paved by different materials: cobblestone and precast concrete plates), Hanuševa street, Case C.

For better correlation between road surface and vehicle vibrations measurement of road surface roughness was also carried out before and after reconstruction of the observed test sections (Case A to C). This method gives best insight into the impact of reconstruction on the level of ride comfort and safety that depends on road surface roughness and is directly correlated to vehicle vibrations.

Suggested and analysed urban road pavement condition determination technology provided a simple road survey (vehicle vibration measurements) as a valuable source of information for traffic and civil engineers on road maintenance requirements.

2. EXPERIMENTAL METHOD AND CONDITIONS

2.1 Vibrations measurement system

The testing platform used in this study was a personal car; OPEL Vectra B1.8, 1.6V (2002). The car was equipped with standard tyres. To collect, record, and analyze the data, a measurement system was designed and installed in the vehicle. It consisted of:

- Accelerometer A1, Brüel & Kjær type 4508B1, 10 mV/g, 0.1 Hz – 8 kHz;
- Accelerometer A2, Brüel & Kjær type 4508B, 100 mV/g, 0.3 Hz – 8 kHz;
- Battery-powered Data Acquisition Unit Brüel & Kjær PULSE;
- Portable computer for data recordings and post-analysis;
- Voice recorder and video camera.

The two accelerometers for vibration measurement were installed at an authorized dealer in Zagreb (Opel AutoWill). The first accelerometer (A1) was mounted on the front right wheel holder (*Figure 1*) and the second accelerometer (A2) was mounted to the chassis immediately next to the passenger seat (*Figure 2*). Vibrations in the vertical direction (perpendicular to the road surface) were recorded using a battery-powered multi-channel Brüel & Kjær PULSE analyzer and the Time Data Recorder program (*Figure 3*). Information regarding some specific qualities during the measurement were recorded by means of a 'voice dictaphone' and a video camera.

Figure 1 - Accelerometer A1 on the front wheel holder

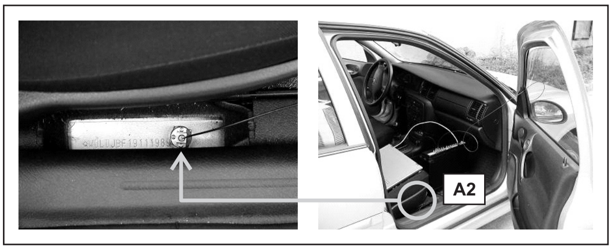


Figure 2 - Accelerometer A2 on the vehicle chassis

Figure 3 - Measuring equipment in the vehicle

2.2 Measurement of road surface roughness

For the research into how much the road surface affects the vehicle vibrations and driving comfort, measurements of the road surface roughness have been recorded. It is well known that the construction or reconstruction of a pavement structure cannot achieve a perfectly even driving surface. However, the permitted deviations of the evenness of a driving surface are de-

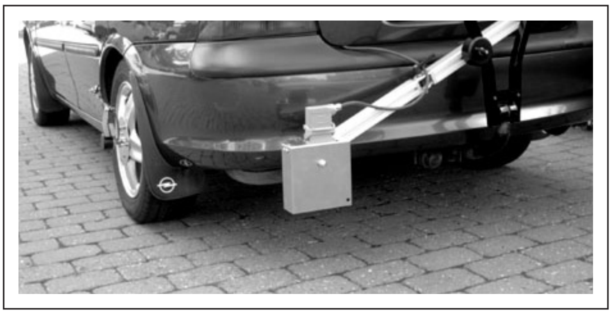


Figure 4 - Greenwood LaserProf device

Table 1 - IRI_{100} values obtained by measurement

Locations		IRI (m/km)	
		Before reconstruction	After reconstruction
A.	Zagreb Avenue (section I)	3.28	1.28
	Zagreb Avenue (section II)	2.08	
B.	Šubićeva - Zvonimirova intersection*	7.52	4.49
	Vukovarska - Držićeva intersection*	7.04	4.72
	Savska - Vukovarska intersection*	5.77	3.80
C.	Ozaljska Street**	9.28	3.63

** Because of the small length of measured section (50 -75 m), IRI_{10} was calculated*

***Before reconstruction (pavement with cobblestone), after reconstruction (pavement with precast concrete plates)*

termined by technical regulations. In accordance with those regulations, measurement of the evenness of the driving surface was carried out on all road sections that are polygons for investigation. Since we wished to ascertain how much the riding comfort on the reconstructed road would improve, we measured the roughness before and after reconstruction. A Laser-Prof inertial profilograph manufactured by Greenwood Engineering was used for the measurement, *Figure 4*.

IRI values obtained by measurement on several specific locations are shown in *Table 1*. As it can be seen from *Table 1*, the evenness of the driving surface on Zagreb Avenue before reconstruction has been observed on two sections. The first section is the older one with rougher driving surface. After the reconstruction the same average roughness level has been achieved on both sections.

3. RESULTS OF VIBRATION MEASUREMENTS

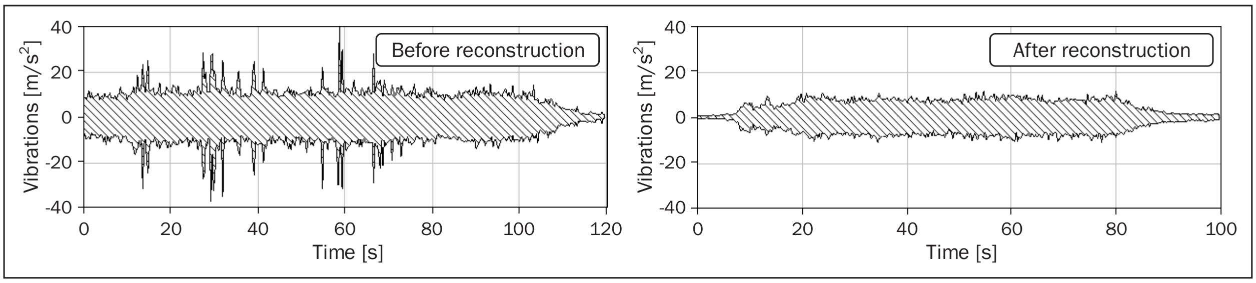
After having mounted the equipment for car vibrations measurements and the survey of traffic surface geometry, the measurement of car vibrations started. During measurement, two persons were in the car: the driver (85 kg, head of research) and the assistant driver (80 kg, engineer controlling the measurement devices).

3.1 Effect of road surface roughness before and after reconstruction (Case A)

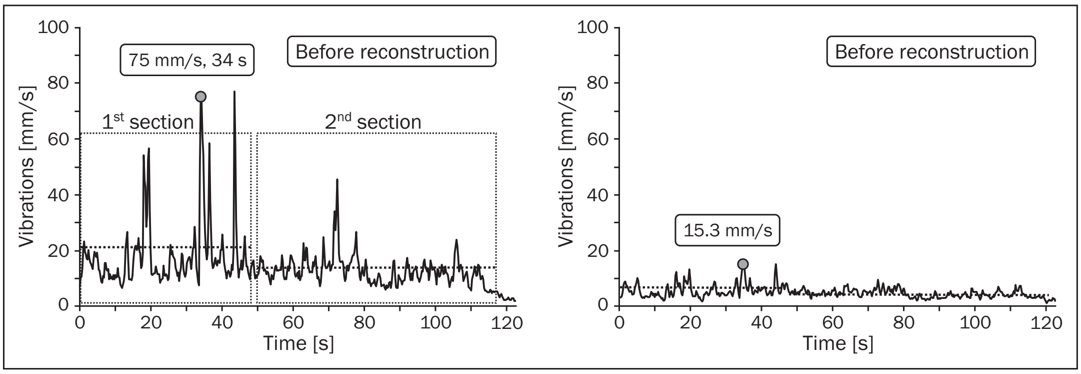
To correlate the pavement roughness condition to recorded vibrations, the measurements have been conducted on Zagreb Avenue, before and after reconstruction. This avenue is a fast city thoroughfare that is the western approach to the City of Zagreb. Due to its function and position in the traffic network, it receives and distributes traffic flow to the central zone of the city and concentrates the outward bound traffic flow from the centre toward the western exit of the city. The road was under construction from the 1950s until 1983. After that time, only maintenance of the worn-out pavement structure was carried out. During 2006 this Avenue was reconstructed.

To increase the flow-through capacity, both basic goals were used; construction expansion of the cross-section of the existing road and installation of intelligent transportation system (ITS) based on the Traffic-Technological Design. During the reconstruction of the road, the pavements were expanded to three traffic lanes in each direction continuously. The reconstruction of the existing pavement structure, in those areas where the lower part was kept, was carried out in such a way that the existing pavement was milled to the depth of 10 to 12cm, and new asphalt layers were placed upon it. In the zones where the road was expanded, completely new pavement structure has been laid with the usual number of asphalt layers. The reconstruction increased the flow-through capacity of the road by 38%, completely realizing the goal of increasing this capacity. Average daily traffic before reconstruction was 65,000 vehicles/day and after reconstruction it is 88,000 vehicles/day (in both directions - on a working day) [9].

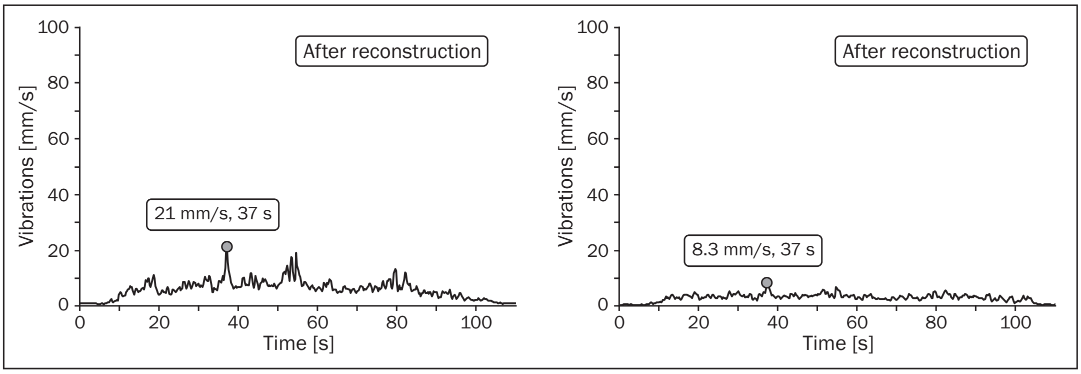
As mentioned, the vehicle vibrations and road surface roughness were measured before and after the reconstruction of the Zagreb Avenue. The measurement of the vibrations of the car wheel holder (*Graph 1*) and the car chassis was carried out continuously at a constant speed of 80km/h. Graphs 2 and 3 present, in the same scale (0-100mm/s), the time profiles of the car wheel holder and the car frame (chassis) vibrations before and after reconstruction. The measured maximum values of wheel holder vibrations before reconstruction were 78mm/s on the 1st section (IRI: 3.28m/km) and 45mm/s on the 2nd section (IRI: 2.08m/km). After the reconstruction, wheel vibrations decreased to 21mm/s parameter (IRI: 1.28m/km). The maximum measured car frame vibrations before reconstruction were 15.3mm/s on the 1st section and 11.2mm/s on the 2nd section. After reconstruction, they decreased to 8.3mm/s. As can be seen in graph 3, the average value of wheel vibrations after reconstruction were not higher than 10mm/s, and the vibrations of the car frame were therefore not higher than 3mm/s.



Graph 1 - Time profile of car wheel holder vibrations (± 40 m/s²)



Graph 2 - Car wheel holder and car frame vibrations before reconstruction (Zagreb Avenue)



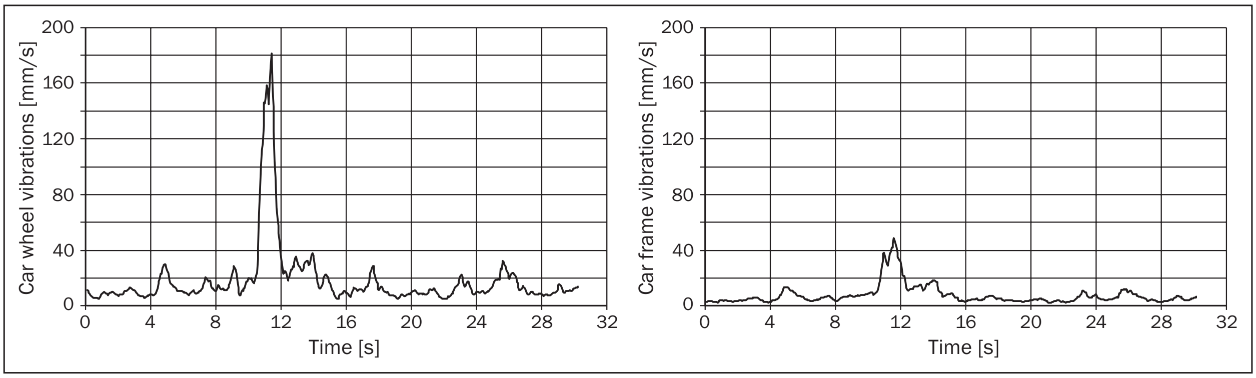
Graph 3 - Car wheel holder and car frame vibrations after reconstruction (Zagreb Avenue)

3.2 Effect of rail-road intersection (Case B)

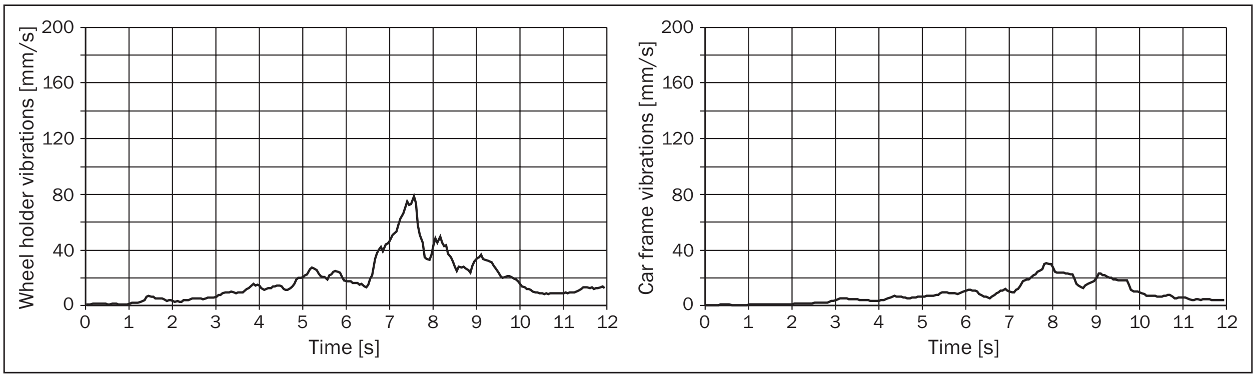
Driving through the intersection of road and tram or railways tracks (rail-road intersection) always causes uncomfortable and unpleasant driving, as well as high car vibrations. Research was conducted on several high-frequency intersections in Zagreb, where there is a large traffic load, both by road vehicles and by the vehicles on tracks. The measurement of IRI parameters on the crossings, in which car vibrations were measured, is presented in *Table 1*. As can be seen on the observed intersection the IRI parameter was measured before and after reconstruction. Vehicle vibrations on all rail-road intersections have been measured with constant vehicle speed of 40km/h. The maximum value of vibration is the result of vehicles crossing over the rails but depends largely on the track pavement material. The considered intersections had different materials for track closure (pavement). The type of rail-road intersection pavement, before and after reconstruction, is presented in *Table 2*.

Table 2 - Type of rail-road intersection pavement

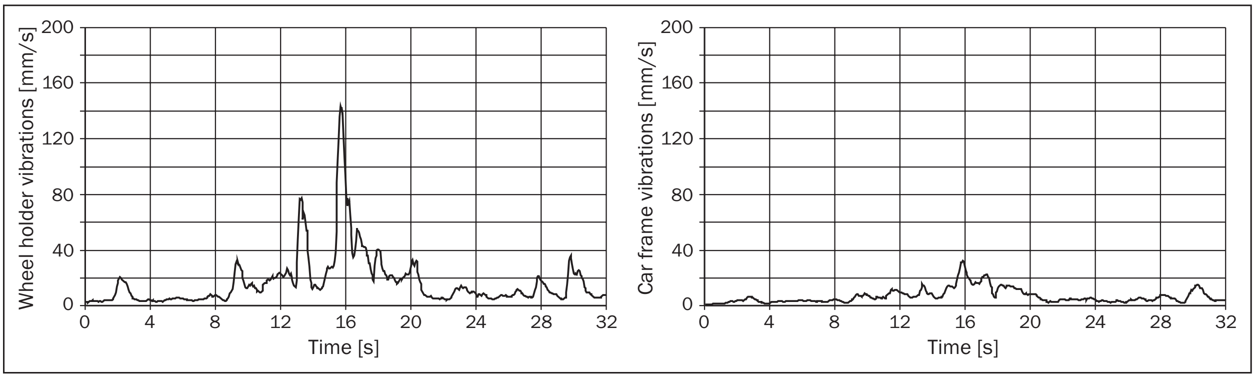
Rail-road intersection	Type of track pavement	
	Before reconstruction	After reconstruction
Šubićeva – Zvonimirova	cobblestone	asphalt
Vukovarska - Držićeva	concrete plates	asphalt
Savska – Vukovarska	asphalt	asphalt



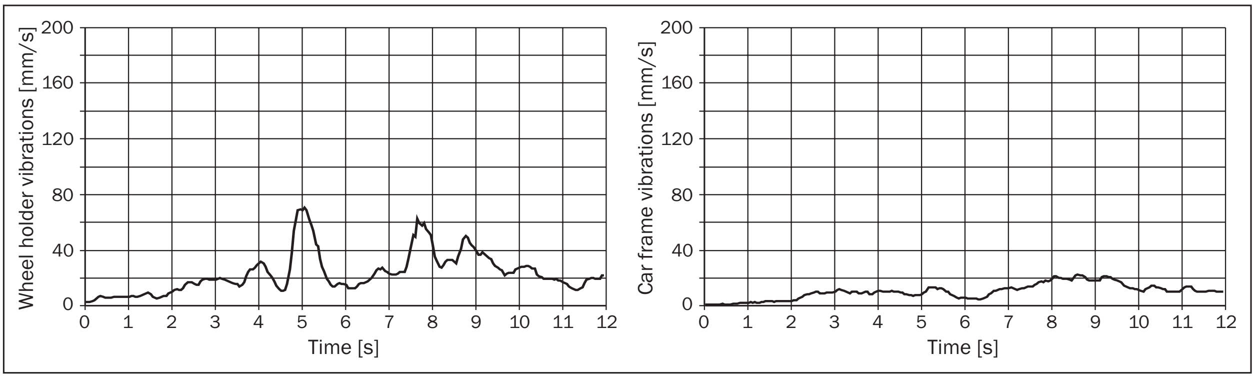
Graph 4 - Vehicle vibrations on Šubićeva-Zvonimirova intersection (before reconstruction)



Graph 5 - Vehicle vibrations on Šubićeva-Zvonimirova intersection (after reconstruction)

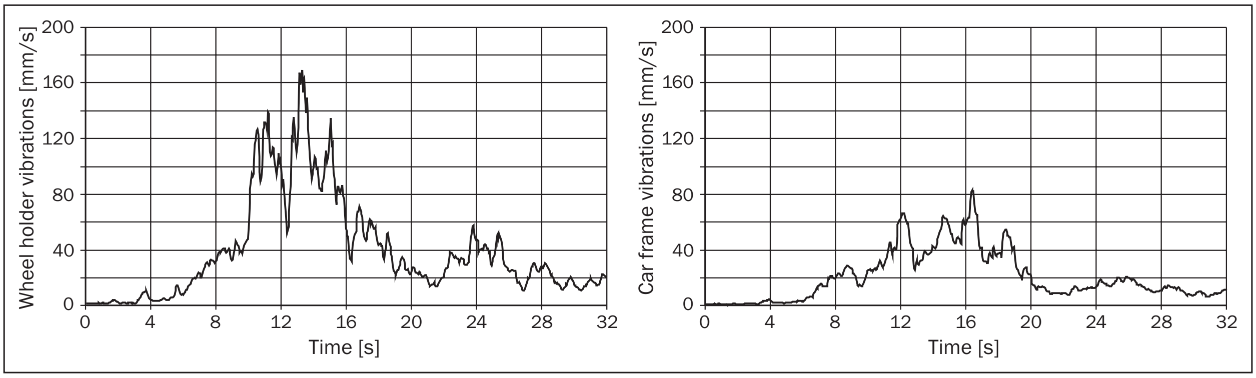


Graph 6 - Vehicle vibrations on Vukovarska-Držićeva intersection (before reconstruction)

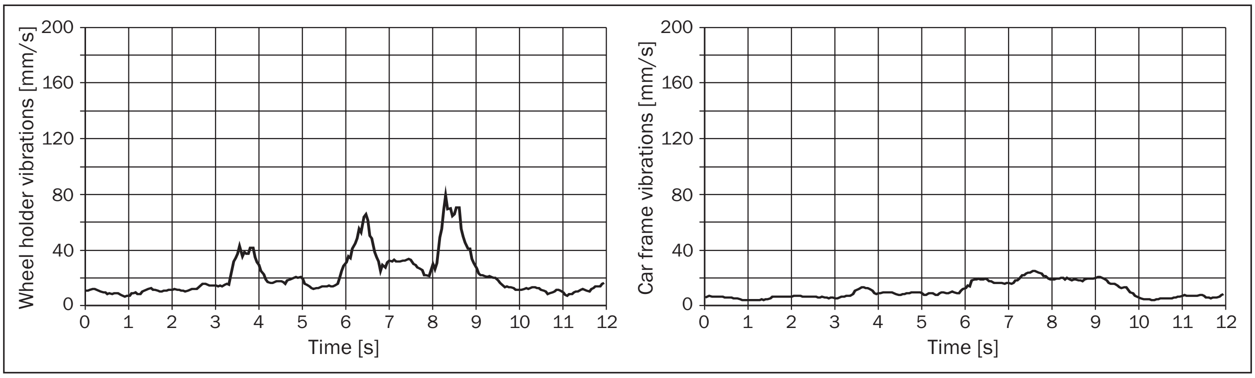


Graph 7 - Vehicle vibrations on Vukovarska-Držićeva intersection (after reconstruction)

The measured vehicle vibrations on Šubićeva-Zvonimirova intersection (before and after reconstruction) are presented in Graphs 4 and 5. The maximum values of wheel holder vibrations were 180mm/s (before reconstruction) and 78mm/s (after reconstruction). Maximum car frame vibrations were up to



Graph 8 - Vehicle vibrations on Savska-Vukovarska intersection (before reconstruction)



Graph 9 - Vehicle vibrations on Savska-Vukovarska intersection (after reconstruction)

48mm/s (before reconstruction) and 30.5mm/s (after reconstruction).

The measured vehicle vibrations on Vukovarska-Držićeva intersection (before and after reconstruction) are presented in Graphs 6 and 7. The maximum values of wheel holder vibrations were 145mm/s (before reconstruction) and 35mm/s (after reconstruction). Maximum car frame vibrations were up to 32.5mm/s (before reconstruction) and 22mm/s (after reconstruction).

The measured vehicle vibrations on Savska-Vukovarska intersection (before and after reconstruction) are presented in Graphs 8 and 9. The maximum values of wheel holder vibrations were 84.7mm/s (before reconstruction) and 35mm/s (after reconstruction). Maximum car frame vibrations were up to 41.2mm/s (before reconstruction) and 12.1mm/s (after reconstruction).

3.3 Effect of tram track pavement (Case C)

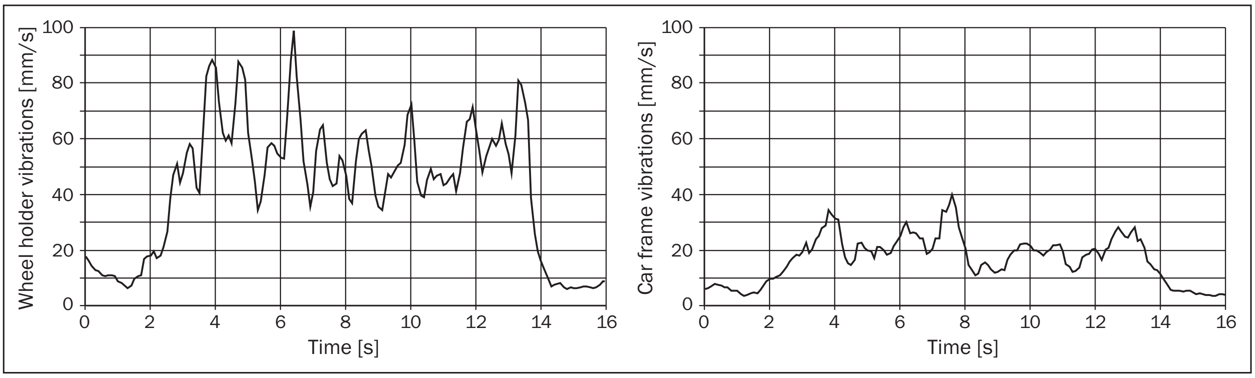
It is a well known fact that on those parts where rail and road vehicles use the same traffic surface because of narrow traffic corridors (the very centre of the city), the rail structure is within the composition of the pavement structure, as shown in *Figure 16*. In such cases, tracks are being paved by certain materials. Concrete filler and final asphalt layer (the same as on road traffic route) are frequently used on rail-road intersection where significant dynamic loads are present due to heavy road freight traffic. On other parts of railway tracks, for the purpose of rail structure maintenance, mounting/dismounting elements for track pavement can be found in frequent use. In the paper, two such cases have been studied, track pavement with cobblestones and track pavement with concrete plates. The paper analyses tramway track in Ozaljska street before and after reconstruction. The IRI measurement showed that in pavements with cobblestones the IRI is 9.28m/km (before reconstruction), while in track pavements with concrete plates, the IRI is 3.63m/km (after reconstruction).

While driving over tram tracks, which are embedded in cobblestones, constantly increased vibrations were measured with a maximum of 98mm/s for wheel vibrations and 40mm/s for car frame vibrations, *Graph 10*. While driving over the tram track, which is embedded in concrete plates, considerably smaller wheel vibrations were measured (maximum 39mm/s), and the car frame vibrations were not higher than 10mm/s, *Graph 11*.

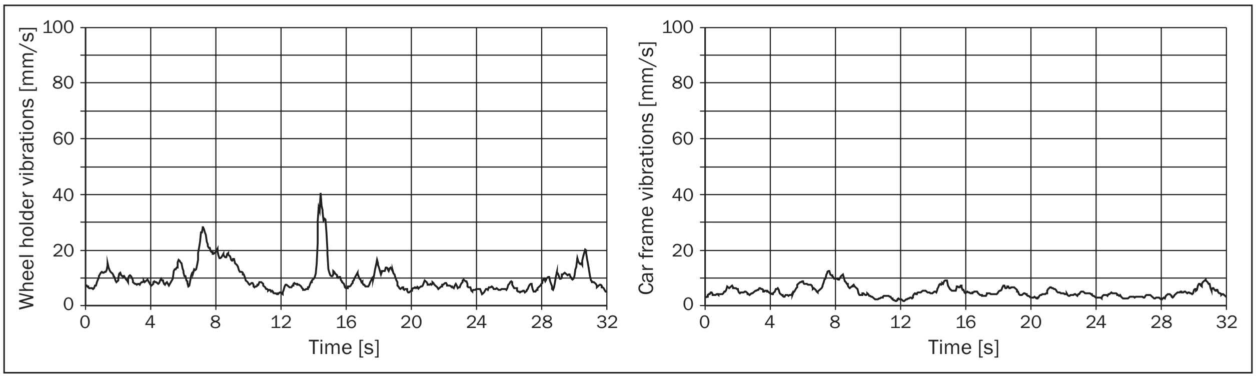
4. DISCUSSION

In order to make relations between the parameters of pavement roughness (IRI) and the measured vehicle vibrations, the average vibrations have been calculated first. As mentioned before, the two sections

Figure 5 - Survey of tram track embedded in road surface



Graph 10 - Vehicle vibrations on tram track pavement with cobblestones

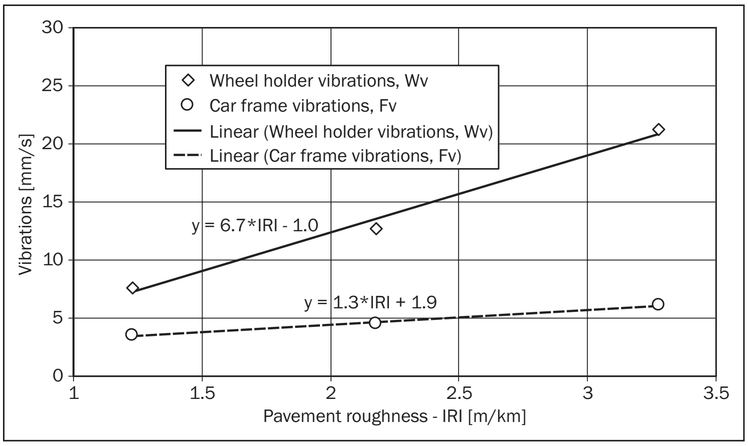


Graph 11 - Vehicle vibrations on tram track pavement with concrete plates

of the Zagreb Avenue have been taken into account before the reconstruction with respect to IRI. This fact is best illustrated in *Graph 2*, where the different values of measured vibrations can be observed. On the first section (from 0 to 48sec) where IRI parameter measures 3.28m/km, the average vibrations on the wheel holder measure 21.2mm/s while vibrations on the car chassis measure 6.1mm/s. On the second section (from 48 to 112sec) where IRI parameter measures 2.18m/km the average vibrations on the wheel holder measure 12.7mm/s while vibrations on the car chassis measure 4.5mm/s. After complete reconstruction of the Zagreb Avenue, the IRI parameter (on both sections) measured 1.23m/km and the average of the wheel holder vibrations was 7.6mm/s, and of the car chassis 3.5mm/s. The results of these analyses are shown in *Table 3*. For the purpose of accurate definition of relations between the parameters of pavement evenness (IRI) and the vehicle vibrations, a correlation has been prepared on the basis of the stated quantities. The results of this analysis are shown in *Graph 12*.

Table 3 - Average of vehicle vibrations in dependence of IRI parameter

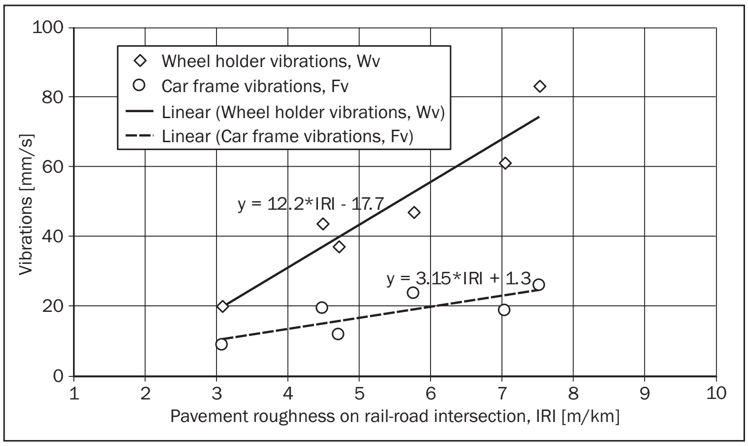
Measurement point	Before reconstruction (section I) (IRI = 3.28 m/km)	Before reconstruction (section II) (IRI = 2.18 m/km)	After reconstruction (IRI = 1.23 m/km)
Wheel holder [mm/s]	21.2	12.7	7.6
Car frame [mm/s]	6.1	4.5	3.5



Graph 12 - Pavement roughness - vehicle vibration correlation (vehicle speed: 80 km/h)

Table 4 - Average of vehicle vibrations in dependence of IRI parameter (rail-road intersection)

Rail-road intersection	Average of vehicle vibrations and IRI parameters					
	Before reconstruction			After reconstruction		
	Wheel holder [mm/s]	Car frame [mm/s]	IRI [m/km]	Wheel holder [mm/s]	Car frame [mm/s]	IRI [m/km]
Šubićeva – Zvonimirova	83	26	7.52	43.9	19.5	4.49
Vukovarska - Držićeva	61	19	7.04	37.3	12	4.72
Savska – Vukovarska	47	24	5.77	20.1	9.3	3.80



Graph 13 - Pavement roughness on rail-road intersection - vehicle vibration correlation (vehicle speed: 40km/h)

Based on the previously measured evenness of the pavement driving surface, the graph estimates the vehicle vibrations quantity. As mentioned in the Introduction, vehicle vibrations are closely connected to the roughness of the road driving surface. If we consider the relative increase in vibrations at the moment of vehicle contact with the humps then it is obvious from *Graph 2* that the increase of wheel holder vibrations is 40 to 60mm/s and the vehicle chassis from 5 to 15mm/s in relation to the average vibrations appear on the pavement without potholes.

If the road-railway crossings are observed, vibrations are noticeably higher. For crossings observed in this research it can be observed that the maximum wheel holder vibrations can reach up to 180mm/s on a poorly maintained crossing. Correct and on-time maintenance of traffic infrastructure, especially of the crossings ensures less vehicle vibrations and consequently higher traffic safety, longer vehicle life span, less vehicle maintenance expenditure and more comfort for the users. The analysis of the average vehicle vibrations on the test polygon analyzed in the paper are shown in *Table 4*.

The average values are calculated only in the zone of crossings (from the moment of contact of the vehicle wheel with the first rail of the first railway track to the moment of crossing of the second rail of the second railway track in the crossing). The period for calculating the average vehicle vibrations in the zone of crossing is between 3 and 4 seconds. Due to the constant speed of 40km/h the period depends on the span between two railway tracks in the crossing.

5. CONCLUSION

The research was conducted with the aim of establishing the relation between surface characteristics of the traffic routes and car vibrations. The vibrations were measured at the limited speed of 40 to 50km/h (traffic routes in the city centre), while on the avenues the limited speed of automobiles during the measurement of vibrations was 80km/h. The chassis vibrations of the car are 4 to 6 times less in relation to the wheel holder vibrations. The above mentioned depends primarily on the vehicles' suspension systems which are unique for different vehicle types or models. Due to that fact it is concluded that vehicle chassis vibrations cannot be used with great reliability in pavement roughness state evaluation.

The registration of vehicle vibrations due to passing over the pavement with transverse cracking, ripples, potholes, patching, block cracking, depression, ravelling, fatigue and joint cracking using this method is very reliable. Measuring the vibrations of vehicles due to irregularities in the direction of the vehicle, such as longitudinal cracking and rutting on pavement, is slightly more complicated. This problem can be solved by installing a number of accelerometers on the vehicle.

The study results could serve to deliver recommendations for the magnitude of permissible vibrations. It is recommended for this manner of car vibrations control to be adopted as the method for making the evaluation on the manner of traffic route management. However, in that case, it would be desirable for the mentioned controls to be performed with one test vehicle, on which accelerometers and profilographs would be installed, whereby data about the surface roughness and driving comfort would be obtained automatically.

If this method is compared to standard procedures for roughness measurements using walking or inertial profilographs, the described method can identify all the irregularities of the pavement. The measuring step of walking profilograph is 241.5mm, while the inertial profilograph can alter the step between 25 to 250mm (usually 50 to 80mm), [6]. The measuring step of the described method is 10 to 25mm depending on the vehicle speed. Vibrations measurements are usually performed at the speed of 4,096 samples per second allowing signal processing of up to 1,600Hz and a time step of 0.25ms. It is also possible to use significantly lower time step. This fact allows observing of the pavement cracks smaller than 25mm which are very important since they affect an increase of vibrations, while the walking or inertial profilographs can skip this type of cracks.

Defining the allowed amount of vehicle vibrations related to traffic safety and driving comfort, the described method allows decision-making concerning reconstruction or intervention planning even without the knowledge on the exact state of pavement. This contributes to rational road management, especially decreasing the maintenance expenditures of urban road networks.

The described procedures of pavement surface quality evaluation represent a new approach compared to standard procedures used today. The method allows simple data collection at the intersections, even on different pavement structures, while standard methods have difficulty in recording and interpretation of such measurements due to a larger time step.

Vibration measurements for the purpose of this research have been performed using a passenger vehicle in order to reduce the price of research. It would be interesting to carry out freight vehicle vibration measurements as well. The measurements of vibrations on both wheels and vibrations of the surrounding buildings should also be taken further into consideration.

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SAŽETAK

ANALIZA VIBRACIJA VOZILA – NOVI PRISTUP OCJENE STANJA KOLNIKA CESTA U URBANIM SREDINAMA

Na cestovnoj infrastrukturi u gradovima odvija se svakodnevno vrlo intenzivan obujam prometa. Opažanje stanja ravnosti kolničke konstrukcije, koje direktno utječe na kvalitetu i sigurnost odvijanja cestovnog prijevoza, a izražava se indeksom ravnosti IRI (International Roughness Index), posebno je otežano u urbanim aglomeracijama u usporedbi s prometnicama izvan naselja. U okviru gospodarenja kolnicima s obzirom na sigurnost i postizanje najbolje moguće udobnosti vožnje, vrlo je važno predvidjeti kada se mora pristupiti rekonstrukciji prometnice. Metoda za ocjenu razine sigurnosti i udobnosti vožnje na gradskim prometnicama prikazana u ovom radu, temelji se na mjerenju vibracija vozila. Navedena mjerenja provedena su na glavnim gradskim prometnicama u Zagrebu (Hrvatska), a obuhvaćene su prometnice s različitim neravninama na voznoj površini. Prikazana se metoda može jednostavno i vrlo lako primjenjivati u okviru gospodarenja kolnicima s ciljem postizanja veće sigurnosti i udobnosti vožnje. Rezultati mjerenja, dobiveni u skladu s ovom metodom, mogu poslužiti kao prijedlog prometnim stručnjacima za donošenje preporuka kod kojih nepravilnosti na kolniku treba pristupiti rekonstrukciji ili održavanju kolnika.

KLJUČNE RIJEČI

ceste u urbanim sredinama, prometni tok, sigurnost, vibracije vozila, ravnost površine kolnika (IRI)

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