VOLUME 3 NUMBER 4 2010

TRANSACTIONS ON TRANSPORT SCIENCES

Ministry of Transport

CDV TRANSPORT RESEARCH CENTRE

CZECH TECHNICAL UNIVERSITY

TRANSACTIONS ON TRANSPORT SCIENCES

Publisher: *Ministry of Transport*, nábř. L. Svobody 1222/12, 110 15 Praha 1, Czech Republic
E-mail: *info@transportsciences.org*
URL: *www.transportsciences.org*

Editorial Office: Olga Krištofíková
Hedvika Kovandová
Jana Zelinková
Vladimír Adamec
Petr Polanský
Irena Zedková

Periodicity: Quarterly
Language: English
Scope: International scientific journal for transport sciences
Print version: ISSN 1802-971X
On-line version: ISSN 1802-9876
Registration Number: MK EČ E 18012

Each paper in the journal is evaluated by two reviewers under the supervision of the International Editorial Board.

The Research and Development Council of the Government of the Czech Republic indexed this journal in the Title List of Peer-Reviewed Journals.

Distributor: CDV – Transport Research Centre, Líšeňká 33a, 636 00 Brno, Czech Republic, journal@cdv.cz.

Assessment of Heavy Metal Pollution (Cd, Cu, Pb, Hg) in Urban Soils of Roadsides in Brno

A. Debnárová & H. Doleța lová Weissmannová*

Institute of Chemistry and Technology of Environmental protection, Faculty of Chemistry, Brno University of Technology, Brno, Czech Republic
** Corresponding author: dolezalova@fch.vutbr.cz*

DOI: 10.2478/v10158-010-0021-1

ABSTRACT: This environmental study is focused on the distribution of heavy metals in the soils of selected localities in Brno. The soils samples were collected near roadsides and the concentrations of Cd, Cu, Pb and Hg were determined with using atomic absorption spectrometry. The contamination of soils from selected localities was evaluated on the basis of the pollution index, contamination factor and degree of contamination; and the limit contents of heavy metals in soils which is listed in the Guidance MȚP Czech Republic were also used for assessing the contamination. Mercury and cadmium have been identified as the main polluting metals in selected localities with a high transport load. The obtained results also confirmed that the environment of Brno can be characterized as an area of uncontaminated to a moderate degree contaminated in relation to the contamination factor and contamination degree of the environment in the case of metals (Cd, Cu, Pb, and Hg).

KEY WORDS: Heavy metal, soil, roadsides, pollution index, contamination factor.

1 INTRODUCTION

Environmental pollution due to human activity in cities is still a hot topic, and this problem has been the subject of many studies. Increased levels of hazardous metals not only affect soil quality, water, and the environment, but also human health. The main sources of air pollution in urban and suburban areas are growing industries (chemistry, metallurgy, electronics, and construction, factories), burning fuel, waste management, and transport (EEA, 2007). With regard to increasing transport, the following factors have the major impact on pollution: traffic volume, the quantity and composition of fuel, road type, type and condition of engines, and transport mode. The rapid increase in cars leads to a lot of pressure on the urban environment and transport is becoming the biggest contributor to pollution in the city (Adamec, 2006). Heavy metals in urban soils exist in various forms, in changed or adsorbed form, which affects their behaviour in soil, especially their mobility and bioavailability (Adriano, 2001). The total concentration of heavy metals in the soil is usually regarded as an indicator of urban environmental quality (Oliva et al., 2007; et al., 2006).

Sources of cadmium in the urban environment are few and there are several sources of Cd accumulation in the urban environment. In fact, most of the cadmium extracted worldwide is used in Ni-Cd batteries, while the remainder is used for the coating and plating of plastics and pigments. Cadmium is also used in the manufacture of automotive radiators and in the manufacture of electronics components. It makes up a part of tires, gasoline, diesel and lubricating oils. Copper is widely used for industrial production and electrical and electronic equipment, which are an emerging source of copper. Therefore, copper tends to accumulate in urban areas. In fact, 2 kg of copper waste is produced per capita each year in Europe. In comparison with other elements, the information on soil mercury is limited, particularly for urban areas. The melting of copper and zinc, coal burning, and waste incineration, and industrial processes, such as the production of chlorine and caustic soda are the most important human activities that can release mercury into an urban environment. Mercury is also released into the environment by fluorescent lamps, thermometers, thermostats, electrical switches, pressure sensors, etc. The urban areas together with mining localities belong to major areas for the accumulation of mercury in the soil (Ajmone-Marsan and Biasioli, 2010, Biasioli et al., 2007).

The selected metals (Cd, Cu, Pb and Hg) are characterized by a high toxicity and have a significant impact on environmental components. To assess the level of contamination indexes such as the pollution index (PI), integrated pollution index (IPI), contamination factor (C_f) and the degree of contamination (C_{deg}) can be used (Loska et al., 2004, Wong et al., 2006).

Pollution index (PI) and integrated pollution index (IPI)

The pollution index (PI) is calculated by dividing the measured concentration of the element by the tolerable limit of the metal and the integrated pollution index (IPI) is calculated using the formula 1.

$$IPI = \frac{1}{N}\left(\frac{M_1}{TL_1} + \frac{M_2}{TL_2} + \ldots \frac{M_n}{TL_n}\right) \qquad (1)$$

where M_1, M_2, M_n are the average concentration of the polluting metals and TL_1, TL_2, TL_n are the tolerable levels for each metals, N is the number of polluting metal considered. Tolerable levels of pollutants (limits) are given in each state legislative document or criteria for soil pollution. The classification of PI values for each metal-contaminated soil was characterized on the basis of criteria such as virtually uncontaminated soils ($PI \leq 1$), moderately contaminated soils ($1 < PI \leq 3$) or highly contaminated soils ($PI > 3$). The integrated pollution index (IPI) of metals characterized the contamination of soils from study area as follows: low contaminated soils ($IPI \leq 1$), moderate contaminated soils ($1<IPI<2$) or high contaminated soils ($IPI > 2$).

Contamination factors and degree of contamination

The contamination factor (C_f) and degree of contamination evaluate soil contamination. The calculation of C_f is made according to equation 2:

$$C_f = \frac{C_M}{C_n} \qquad (2)$$

where C_M is the mean concentration of metals from at least five samples and C_n is the preindustrial concentration of the individual metal. The preindustrial concentration is expressed as the concentration of elements in the Earth’s crust. The classification is in relation to the C_f index: $C_f < 1$ low contamination factor indicating low contamination, $1 \leq C_f \leq 3$ moderate contamination factor, $3 \leq C_f \leq 6$ considerable contamination factor and $6 \leq C_f$ very high contamination factor. The sum of contamination factors (C_f) for all metals represents the contamination degree (C_{deg}) of the environment. The classification of the contamination degree: $C_{deg} < 8$ low degree of contamination, $8 \leq C_{deg} < 16$ moderate degree of contamination, $16 \leq C_{deg} < 32$ considerable degree of contamination, and $32 \leq C_{deg}$ very high contamination factor.

2 MATERIALS AND METHODS

2.1 Study area and sampling

Brno (49° 12' N – 16° 34' E) is located in Moravia and it is the second largest city in the Czech Republic, the population this city is 405 337 people and population density is 1 760.65 people per km^2 (2009). The city itself lies in the basin of the Svratka and Svitava rivers. Brno has been an important long-term crossroad not only in the Moravian region, but also for the Czech Republic, due to its specific geographical situation. The high density of roads and the main Czech expressway (D1) results in pollution by heavy metals. The city is situated at the crossing of expressways D1 (Prague, CZ) and D2 (Bratislava, SK), and expressways R52 (Vienna, A) and R43 (Svitavy, CZ). For this study, localities with various incidence of road transport and industry were chosen for the evaluation of soil contamination within Brno. Traffic is characterized as high and the number of vehicles of up to 48,000 / per day. The simplified traffic situation in Brno is shown in Figure 1, where the sampling sites are also marked.

Table 1: The basic characteristics of sampling sites.

Localities	**GPS (latitude, longitude)**	**Basic characteristic**	A_h **[m]**
L1 Cimburkova (Ponava)	49°13'4.392"N, 16°36'19.454"E	Traffic localities Road R43 (to 1.5 km)and R42 (to 0.4 km) and Královopolská a.s.	218
L2 Koliště (centre)	49°11'56.859" N 16°36'41.161" E	Traffic locality with usual traffic jams, city ring road, roadside (20m from road)	215
L3 Botanická (centre)	49°12'16.688"N, 16°36'7.875"E	Traffic locality/park (10m from road)	232
L4 Purkyňova (Medlánky)	49°13'53.514" N 16°34'35.22" E	Peripheral urban locality, 0.5 km to road E461, 640	260
L5 Průmyslová (Slatina)	49°10'16.673" N 16°40'18.861" E	Peripheral urban industrial zone (distribution, trade and storage buildings), 0. 8 km from D1, E462 and E50	340
L6 Jedovnická (Juliánov)	49°11'24.255" N 16°39'52.332" E	Peripheral zone, 2 km from incinerator SAKO Brno a.s ., 50 m from road 373	272
L7 Údolní (centre)	49°11'53.552" N 16°35'53.637" E	Traffic locality, 80 m to crossroads Úvoz - Údolní	231
L8 Opuštěná (Trnitá)	49°11'7.716" N 16°36'46.827" E	Traffic locality, bus terminal (Zvonařka, 0.1 km distance), city circle road, roadside 20 m road	200
L9 Vídeňská (Štýřice)	49°10'24.189" N 16°35'47.548" E	Traffic locality, city ring road, roadside (0.14 km from E461 and 52)	212
L10 Okruțní (Lesná)	49°14'12.461"N, 16°36'56.873"E	Periphery of city, 2 km to R43, without urban built-up area	259

A_h – Altitude; height above sea level of locality

The selected sites are typical for different levels of traffic and are situated in both the central part of the city, peripheral part of city, and the city ring road of Brno. The aim of this study was (1) to determine the concentrations of Cd, Cu, Pb, and Hg in urban soils near roads, (2) to assess the degree of heavy metal pollution in urban soils using various indices that describe the degree of contamination of the site and the degree of contamination in the localities with regard to long-term pollution stress.

Samples were collected six times from each site from October 2009 to March 2010. A total of 60 samples were collected from 10 localities and sampling was conducted as described in ISO 10381-5:2005. Plastic containers were used to collect and store samples. The climatic conditions of sampling were also recorded (temperature, moisture). Soil samples were obtained that were taken from a depth of 20 cm, sieved through a 2 mm mesh, and dried at 40°C. For each sample (sample number 60) dry weight was determined at 105°C.

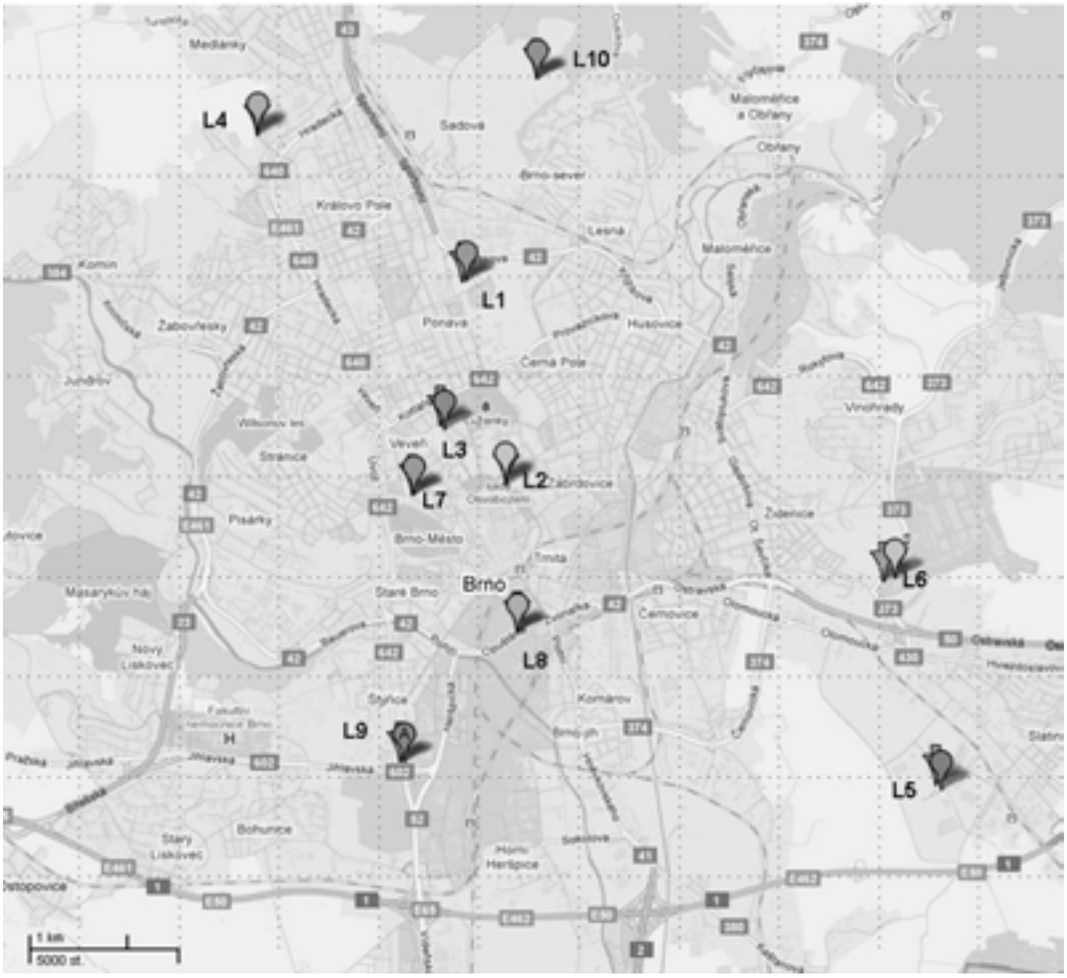

Figure 1: Map of Brno with sampling localities and a simplified scheme of the traffic situation (adapted from Mapy CZ).

2.2 Chemical analysis of soil samples

Extract acidic soils were prepared for analysis from 5 g soil with 50 ml 2M HNO_3 (pa, Lachema). This suspension was shaken continuously for 16 hours at 22 ± 1°C and then filtered through a 0.45 μm membrane filter. Blanks were prepared in the same manner as soil samples. Simple acid extraction represents the ease of mobility of trace metals in the soil.

The concentrations of Pb and Cu were determined by using flame atomic absorption spectrometry (F AAS; SpectrAA 30, Varian). The model AAS ZEEnit 60 (Analytic Jena) atomic absorption spectrometer was equipped with a transversely-heated graphite furnace (GF AAS) and Zeeman background corrector. This spectrometer was used for the determination of Cd. The background and interference of matrix were monitored throughout the analyses.

The atomic vapour generator AMA254 was used for the accurate determination of trace mercury in the solid soil samples. Standards of metals were prepared with HNO_3 from 1 ± 0.002 g/L solution of lead, cadmium and copper (Analytica, s.r.o. Praha). The standard of mercury was prepared using 0.5 ml concentrated HNO_3 (p.a.), 0.5 ml concentrated HCl and 0.5 ml solution $K_2Cr_2O_7$ (1%) and adding 10 µl of calibration standard mercury with a concentration of 1g/L in 50 ml. The soil samples were analyzed three times and the data were considered acceptable when RSD was less than 10%. The analytical procedure of the method used was verified using certificated standard reference materials (CRM CZ 7004 – Loam Soil, Analytika spol. s.r.o.).

3 RESULTS AND DISCUSSION

Results from chemical analysis of heavy metals in soils samples and statistical treatment (means, medians, ranges, standard deviations SD) are given in Table 2. The obtained data shows the wide ranges of the concentration of metals. The concentration of Cd in the urban soils was in the range 0.05 – 0.60 mg/kg with a mean 0.21 mg/kg and median 0.13 mg/kg. The total concentration of Cu was in the range from 5.41 to 25.33 mg/kg with a mean 12.42 mg/kg and median 9.63 mg/kg. The total concentration of Pb in soil samples varied from 10.84 mg/kg to 66.62 mg/kg with a mean 30.75 mg/kg and median 30.14 mg/kg. The concentration of Hg ranged from 0.05 to 0.92 mg/kg with a mean 0.37 mg/kg and median 0.30 mg/kg.

These wide ranges of metals in urban soils are due to the long-term accumulation of metals from polluting sources in the urban environment, such as mobile sources (transport) and stationary sources. The statistical date from the analysis marked in mean, median, SD suggest that the data come from different contaminated localities and also that the distribution is not normal. Results indicated a high potential of anthropogenic influences on the concentration of heavy metals. The highest concentration of Cd and Cu were found in samples from localities L7 (80 m to crossroads Úvoz - Údolní) and L8 (bus terminal Zvonařka, 0.1 km distance from L8), and in comparison L7 > L8. The maximal concentration of Pb and Hg were identified in samples from localities L8 and L7 (L8 > L7) as is shown in Figure 2.

The high levels of metals in study localities arise from high traffic stress at localities. Localities L7 with high transport at the crossroads Úvoz - Údolní and L8 - main bus terminal Zvonařka and its high stress from transport are highly contaminated by heavy metals. Locality L2 is also highly contaminated with lead, mercury, and copper. This locality (L2) Koliště is part of the city circle and typically has high traffic stress. The minimal concentrations of metals were found in the localities L6, L9 and L10; these localities are on the peripheral zone of city and the contents of metals were generally low. The method of assessing the contamination of localities for each contaminant is possible with the use of various indices, such as index pollution and integrated index pollution, that are known in the environmental field. The pollution index PI is defined for each metal as the ratio of heavy metal concentration in the soil to the limit value of the metal.

The index is calculated for each element for all localities together and the values represent the contamination of all areas, which means the total pollution of the city of Brno by metals and this is represented by the integrated pollution index. The calculation of the index for each metal for each sampling locality represents the pollution index and its means the possibility of comparing individual localities and the contribution of metals.

Considering that the limits of concentration of heavy metals in urban soils listed in the Guidance MŢP (1996), the indices of pollution (PI) of metals also integrated pollution index (IPI) for each localities and area Brno also were calculated with using limit contents of metals in soils.

Table 2: Chemical analysis of soil samples from 2009-2010 (statistics – mean, median, range, standard deviation SD for heavy metal concentration mg/kg in urban soils).

Locality	Statistics	Cd	Cu	Pb	Hg
L1	Mean	0.11	18.39	38.45	0.48
	Median	0.14	16.50	43.98	0.35
	Range	0.05-0.15	13.36-25.33	26.25-45.12	0.30-0.81
	SD	0.03	2.25	4.59	0.08
L2	Mean	0.21	19.77	53.06	0.71
	Median	0.26	20.93	51.02	0.73
	Range	0.08-0.28	19.77-21.65	50.63-57.45	0.56-0.84
	SD	0.07	0.36	2.07	0.11
L3	Mean	0.24	10.83	41.35	0.52
	Median	0.21	10.26	41.34	0.52
	Range	0.11-0.41	9.55-12.69	40.85-41.86	0.41-0.64
	SD	0.0.9	0.56	3.28	0.08
L4	Mean	0.13	10.35	19.40	0.13
	Median	0.12	8.37	20.12	0.14
	Range	0.12-0.14	7.84-14.5	17.14-20.95	0.10-0.16
	SD	0.02	0.95	1.01	0.05
L5	Mean	0.09	7.67	15.99	0.10
	Median	0.09	7.39	16.07	0.10
	Range	0.05-0.15	6.97-8.65	12.85-19.07	0.07-0.13
	SD	0.01	0.16	0.41	0.05
L6	Mean	0.07	6.11	15.77	0.08
	Median	0.09	6.05	16.07	0.07
	Range	0.04-0.10	5.41-6.88	13.20-18.6	0.05-0.12
	SD	0.02	0.37	0.98	0.02
L7	Mean	0.41	21.98	40.66	0.47
	Median	0.47	21.33	40.17	0.45
	Range	0.17-0.60	20.61-24.02	31.26-50.55	0.43-0.45
	SD	0.05	1.22	2.24	0.10
L8	Mean	0.31	19.73	54.12	0.83
	Median	0.35	19.81	54.06	0.80
	Range	0.19-0.40	17.51-21.87	41.69-66.62	0.77-0.92
	SD	0.03	1.44	8.28	0.14
L9	Mean	0.11	9.68	13.27	0.11
	Median	0.11	8.99	12.31	0.08
	Range	0.08-0.14	8.80-11.25	10.84-16.66	0.06-0.19
	SD	0.01	0.86	1.55	0.04
L10	Mean	0.10	4.64	13.37	0.14
	Median	0.11	4.61	12.38	0.14
	Range	0.08-0.12	3.66-5.66	12.23-15.50	0.12-0.17
	SD	0.01	0.27	2.22	0.01

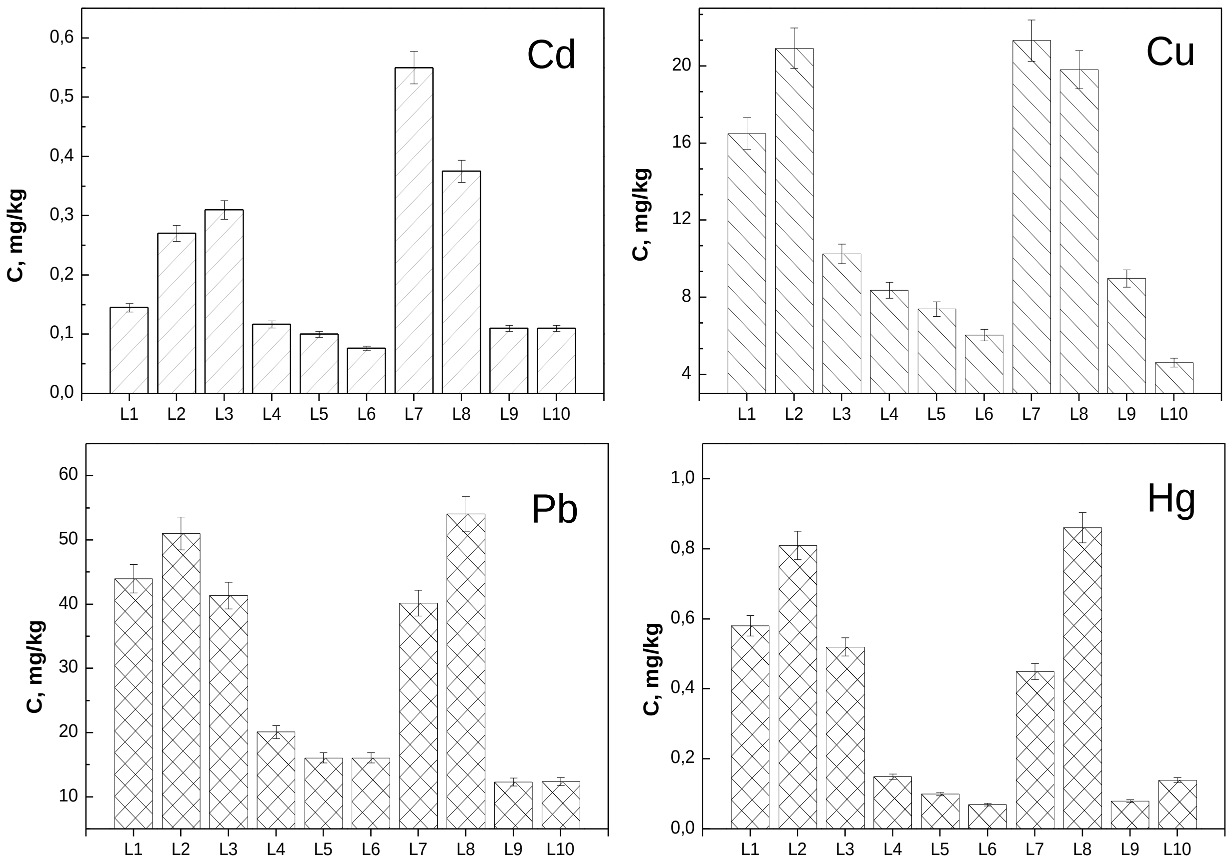

Figure 2: The mean concentration of metals (Cd, Cu, Pb, and Hg) in urban soils samples in localities L1-L10.

The limit concentration of metals listed in Guidance MŢP according to criteria A are as follows : Cd - 0.5 mg/kg, Cu - 70 mg/kg, Pb - 80 mg/kg and Hg – 0.4 mg/kg. Criteria A approximates the natural content of controlled substances in nature. Exceeding the criteria is considered a component of pollution of the environment, except in areas with higher levels of natural substances of concern. Criteria B are designed as a level of metal content, above which it is necessary to further address the pollution. Exceeding the B criteria requires the identified pollution sources and determines its effects and decides on further exploration and the start of monitoring of elements. According to criteria B the content limit of metals in soil are the following : Cd - 10 mg/kg, Cu - 500 mg/kg, Pb - 250 mg/kg and Hg – 2.5 mg/kg. Exceeding criteria C means that pollution has a significant risk to human health and components of the environment, the limited contents of metals in this criteria are : Cd – 20 mg/kg, Cu - 600 mg/kg, Pb - 300 mg/kg and Hg – 10 mg/kg.

The pollution index PI of Cd, Cu, Pb, and Hg varied depending on the type of metal, soil, and locality. The PI value of Hg according to criteria A varied from 0.17 (L6) to 2.15 (L8), criteria B from 0.02 (L6) to 0.34 (L8), and criteria C from 0.007 (L6) to 0.086 (L8). In the case of Pb, using tolerable limit in criteria A the PIs were in the range 0.15 (L10) – 0.67 (L8), in criteria B PIs were from 0.04 (L10) to 0.22 (L8), and using criteria C PIs varied from 0.04 (L10) to 0.18 (L8). The PIs of Cd varied according to criteria A 0.22 (L9, L10), 1.1 (L7); criteria B 0.01 (L9, L10), 0.05 (L7); and criteria C $5.5.10^{-3}$ (L9, L10), $1.8.10^{-2}$ 1.1 (L7). The PI value were exceeded only in the case of mercury for localities L8 (2.15), L2 (2.02), L1 (1.45), L 3 (1.30) and L7 (1.12) when using criteria A. The data obtained show that in the case of mercury when using criteria A the calculated PIs are over 1, which means that localities can be considered to be moderately contaminated by mercury. The pollution indices of other metals in other localities did not exceeded the limit value 1, which means that the localities are unpolluted when using the criteria in Guidance MȚP.

Figure 3 shows the integrated pollution indices (IPI) for each locality and the total IPI of the Brno area; the IPI varied depending on the locality. The highest IPI were found for localities L8 (0.96), L2 (0.87) and L7 (0.76) when using the tolerable limit in criteria A; a typical high transport load characterized these localities. Figure 3 shows that no case exceeded the value of the IPI - 1 when using the limit contents of metals in criteria A, B, or C (MȚP, 1996), which means that the studied localities can be considered unpolluted, and that Brno can also be considered to be an unpolluted city in relation to the pollution index, integrated pollution index when using the limits contents of metals listed in Guidance MȚP.

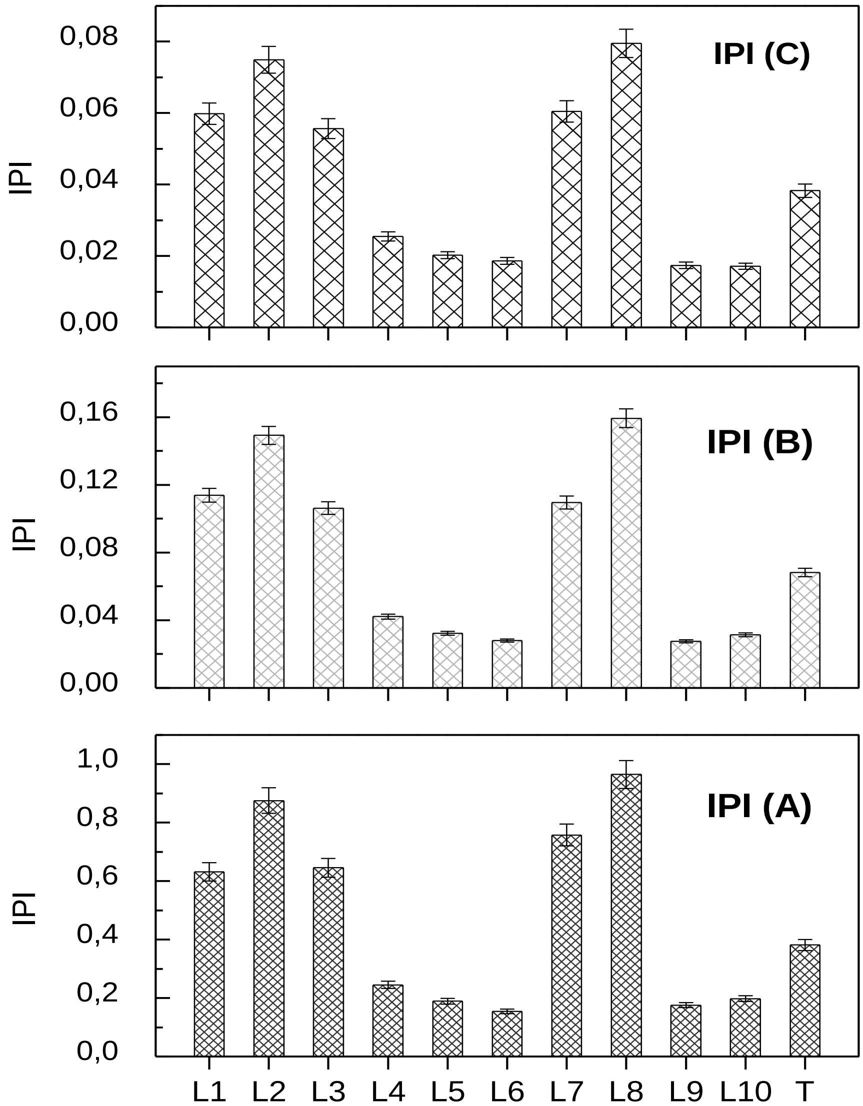

Figure 3: The IPI for localities L1-L8 and T (total IPI for area Brno) in relation to criteria A, B, and C in Guidance MŽP

The contribution of metals to pollution for Brno localities was calculated from the contamination factors C_f of metals that are represented in Figure 3. The preindustrial concentrations of elements (Loska et al., 2004) are used for the calculation of the contamination factor C_f that reflects the long-term effect of pollution to the area. The majority of the contribution to pollution by mercury (C_f – 10.75) and lead (C_f –3.18) was found at locality L8. The main contribution to pollution by cadmium (C_f – 5.5) was confirmed in locality L7.

These contamination factors refer to the pollution of localities L1-L10 and its range from low contamination ($C_f < 1$) to very high contamination $6 \leq C_f$. The value 6 was exceeded in the case of mercury in localities (L1,L2,L3 and L8). The high transport load and frequent traffic jams are typical for these localities. The contamination factors decreased Hg > Cd > Pb > Cu.

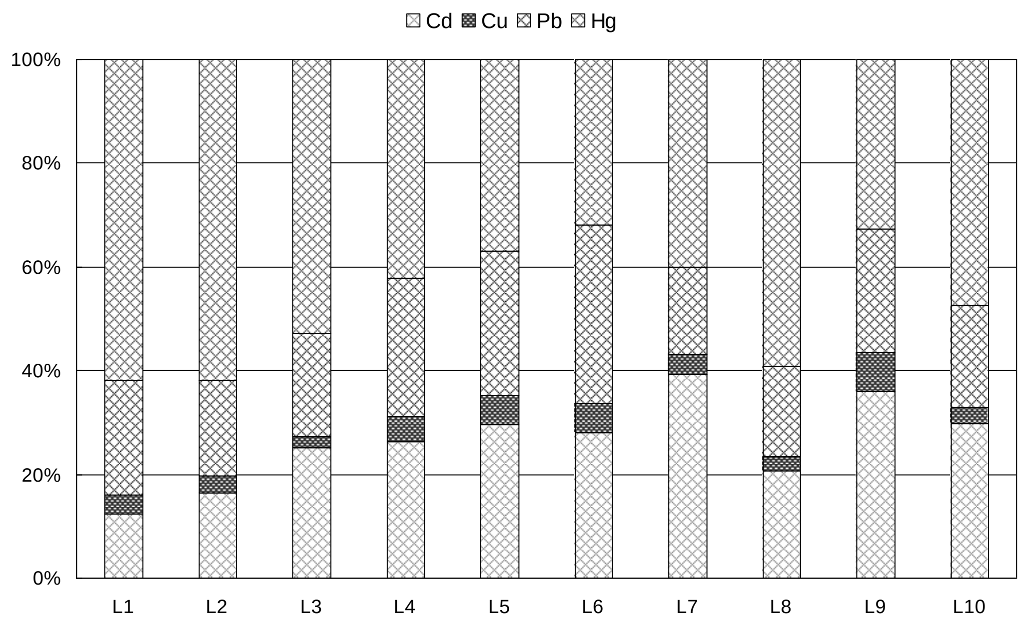

Figure 4: The contribution of Cd, Cu, Pb, and Hg to pollution for the studied localities L1-L10.

The contamination degree (C_{deg}) of the environment when expressed as a sum of the contamination factor (C_f) for all metals confirmed that the total environment in the studied area has been characterized as having a moderate degree of contamination (mean of C_{deg} = 8.99). The maximal contribution of the degree of contamination was found for mercury and lead.

The calculated Pearson's correlation of metals indicates a very strong positive correlation among the Cd, Cu, Pb, and Hg. The values of Pearson's correlation coefficients are over 0.5. A very strong correlation is between Pb and Hg (r^2 = 0.979) and this significant correlation reveals their common sources. A low correlation was found for Cd and Hg (r^2 = 0.642).

4 CONCLUSION

The obtained results show the impact of anthropogenic activities on the environment, mainly the influence of transport on the pollution of soils in the urban area. The data confirmed that the highly toxic metals cadmium and mercury are a major contribution to metal pollution. The localities with typical high transport stress are characterized with high contents of metals and long-term and continuous pollution of the area. These results were confirmed by the contamination factors and also the degree of contamination. The studied localities were selected and characterized according to varying traffic load, population density, or by occurrence of organizations and businesses with a potential impact on the environment. Localities with a greater frequency of automotive transport (Opuštěná L8, Koliště L2, Údolní

L7) were included in selected localities, for which high contents of metals were confirmed and these localities were marked as contaminated localities in Brno. The other localities were Cimburkova (L1) which is adjacent to an establishment producing emissions (Královopolská a.s.) and Jedovnická (L6), which is near the SAKO Brno a.s. (incinerator). The contamination by metals were low in these localities. The content of mercury, lead, copper, and cadmium in soils corresponds mostly to the situation at the site, showing that the majority contribution of contamination is transport.

The concentrations of metals in soils were compared with Guidance MȚP and the result is that the Brno belongs to a practically uncontaminated area. More accurate results confirmed the contamination factor and degree of contamination, and that Brno localities belong to an area with a moderate degree of contamination as concerns cadmium, cooper, lead, and mercury.

5 ACKNOWLEDGEMENTS

This research has been supported by Project FCH-S- 11-2.

REFERENCES

Adriano, D.C., 2001. *Trace elements in terrestrial environments: Biogeochemistry, bioavailability, and risks of metals*. Springer-Verlag, New York.

Ajmone-Marsan, F., Biasioli, M., 2010. *Trace Elements in Soils of Urban Areas*. Water Air Soil Pollut, vol. 213, pp.121-143.

Adamec, V., et. al.: Výzkum zátěţe ţivot ního prostředí z dopravy. (Závěrečná zpráva projektu VaV CE 801/210/109). Brno: 2006, CDV, pp. 86.

Biasioli, M., Grčman, H., Kralj, T., Madrid, F., Diaz-Barrientos, E., Ajmone-Marsan, E., 2007. *Potential toxic elements contamination in urban soils: a comparison of three European cities.* J Environ Qual, vol. 36, pp. 70-79.

European Environmental Agency, 2007. Transport and environment: On the way to a new transport policy. TERM 2006: Indicators tracking transport and environment in the European Union. EEA Report No. 1/2007.

Guidance MȚP, 1996. Kritéria znečištění zemin, podzemní vody a půdního vzduchu dle metodického pokynu Ministerstva ţi votního prostředí ze dne 31.července 1996.

Loska, K., Wiechulab, D., Korusa, I., 2004. *Metal contamination of farming soils affected by industry.* Environ Int, vol. 30, pp. 159- 165.

Mapy CZ – Google mapy Česko [online]. [cit. 2010-01-02]. URL: < http://maps.google.cz/ >.

Oliva, S.R., Espinosa, A.J.F., 2007. *Monitoring of heavy metals in topsoils, atmospheric particles and plant leaves to identify possible contamination sources*. Microchem J, vol. 86, pp. 131-139.

Wong, C.S.C., Li, X., Thornton, I., 2006. *Urban environmental geochemistry of trace metals.* Environ Poll, vol. 142, pp. 1-16.

Critical Infrastructure Safety Management

D. Procházková*
Institute of Security Technologies and Engineering, Faculty of Transport Sciences, Czech Technical University, Prague
** Corresponding author: prochazkova@.fd.cvut.cz*

DOI: 10.2478/v10158-010-0022-0

ABSTRACT: Critical infrastructure is a set of mutually interconnected networks, i.e., the systems of various sectors of a human system. An interconnection of systems means their mutual dependence. Therefore, in connection with safe critical infrastructure and with sustainable development potential, it is necessary to solve several problems, namely the safety of partial infrastructures and the safety of a set of mutually dependent infrastructures. With regard to present knowledge we know that the optimum safety of the set of infrastructures is not the set of optimum safeties of partial infrastructures, and, therefore, we must search for a solution in a different way. The work shows a possible approach for solution acquisition. The paper searches for the principles for safety management of critical infrastructure by logic analysis and the synthesis of present findings and experiences.

KEY WORDS: Critical infrastructure, interdependences, safety, dependability, vulnerability.

1 INTRODUCTION

From the societal viewpoint critical infrastructure represents mutually interconnected networks and systems that include the identified sectors and institutions (including humans and procedures) that provide the reliable flow of products and services substantive for defensive and economic safety, which is understood as the state's capability to compete on global markets, while being on an acceptable level of real public income, and the public administration functioning on all society levels (Moteff et al. 2003). This means that the critical infrastructure is a set of partial infrastructures from different sectors of a human system (see e.g., act No. 183/2006 Col.), that are composed of physical elements and of processes that used these elements for the fulfilment of the tasks of each partial infrastructure. The functionality of this set of partial infrastructures predetermines the human system safety (Prochazkova, 2007a). It is caused by the fact that to economic safety are joined other ones (Moteff et al. 2003), the physical safety that is connected with risks caused from disasters of all kinds, and the cyber safety that is connected with disasters affecting computer networks. Individual items of each infrastructure, according to this work, are subdivided into elements and typical processes according to the distribution, storage, payments, recycling, data transfer, transport, etc.

Critical infrastructure and critical technology in the human system ensure services in a territory, i.e., a certain quality and hierarchy of public services. A measure of the level of services in a territory consists of a judgement of the different sorts of services that have a different importance from the viewpoint of life and the security of humans in an integral sense. In reality there are different sorts of services are ensured by different partial infrastructures that are dependent because, among them, there are interdependences. This fact always manifests during severe disasters (beyond design disasters) when the beyond standard preventive measures are only implemented in special cases in harmony with the legislative demands, and also protective systems, built into the frame of emergency and crisis managements, are only created for selected protected interests (human lives and health, property). Vulnerabilities of partial infrastructures induce cascades of phenomena that cause the failure of other infrastructures, i.e., when the loss of services in territory has secondary impacts on humans and property, so-called interdependences are shown, e.g., in the workplace (Prochazkova, 2007b). This means that in human system safety management the links going across the individual partial infrastructures and across the critical infrastructure and across the human system have not yet been sufficiently considered. For the security and sustainable development of humans it is necessary to solve this problem, and, at least, to remove or to reduce to an acceptable level the secondary and higher order impacts in impact chains that are connected with the start of the occurrence of real disasters (Prochazkova, 2007b). For this reason in practice significant features of critical infrastructure have been followed, understood as a system created by the connection of partial infrastructure systems, that predetermined its functionality and that are mutually dependent. Only with the application of measures that consider the above-given facts is it possible to ensure the quality governance of public affairs in the territory and to fulfil the age-old human dream, i.e., the security and sustainable development of territory and of human society. All of the above-mentioned, and to be mentioned, facts for critical infrastructure are also valid for critical technologies.

In other words, critical infrastructure is the physical (technical and material), cyber, and organisational subsystems of a human system that is necessary for ensuring the protection of human lives, health and security, property and the minimal development of the economy and the administration of the state. The subsystems of critical infrastructure and their number have not been stable in the world (Prochazkova, 2007b). With regard to the documents accepted by the Safety Board and Government of the Czech Republic in 2002 critical infrastructure includes such items as: the energy supply system, the water supply system, sewer system, transport system, communication and information systems, the banking and finance system, emergency services (police, fire rescue service, medical rescue service), basic services (food supply, waste liquidation, social services, funereal services), industry, agriculture, state and regional administrations. Each of the given items is a system with elements, links and flows determined by infrastructure nature. In further text we use a recent concept that the critical infrastructure safety includes both the functionality and the reliability of critical infrastructure.

The aim of the paper is to summarize present knowledge and experiences on critical infrastructure, to judge the role of technical factors and to apply logic methods for the derivation of principles for critical infrastructure safety management from the viewpoint that critical infrastructure is protected against internal and external disasters, and, simultaneously, does not threaten its vicinity and correctly fulfils the expected functions for territory.

2 ASPECTS CONNECTED WITH CRITICAL INFRASTRUCTURE SAFETY

From the above-given description of critical infrastructure it follows that the critical infrastructure is a system composed of mutually interconnected systems. In this coherence it is important that mutual interconnection means dependence. The safety of each system, understood as the set of measures that ensure the safe infrastructure that can sustainably develop depends, of course, on the infrastructure nature. The system safety inherently includes the system protection. The safety of the system that is a set of mutually dependent subsystems is predetermined not only by the safety of the individual subsystems, but also by the character of mutual interconnections.

According to the work (Stein et al. 2003) the interconnection means the dependence of at least two subsystems. By means of this interconnection the condition of one subsystem influences or correlates with the condition of other subsystem. The given definition can be extended by the condition of mutually sharing the several physical elements or processes with those elements or processes that can be situated in a given territory. Therefore, the mutual dependence in the territory may be physical, cyber, logical and regional.

It simultaneously holds:

1. Partial infrastructures are physically mutually dependent if the condition of one of them is dependent on a material output of the other.
2. Cyber mutual dependence means that the condition of one infrastructure depends on information from the other. Cyber mutual dependence requires the existence of information infrastructure.
3. Infrastructures are regionally and mutually dependent if the events in a region can change the conditions of partial infrastructures.
4. Logical mutual dependence means that the condition of one partial infrastructure depends on the condition of the other with the fact that a mechanism of interconnections is not physical, cyber or regional. It takes the dependences transferred through flows created by rules, finances, legislative etc., e.g. finance markets.

In the work (Stein et al. 2003) there are characteristics of partial infrastructures completed by other items when there are the types of malfunctions and failures (cascade and escalation malfunctions, defect for one cause – e.g., natural disasters), the operation conditions (normal, abnormal, critical), the measure of the tightness of relations and interconnections (free, tight, complex) and the critical infrastructure characteristics (time, spatial, organisational, proprietary and institutional).

As a consequence of mutual dependence the defect or failure of one partial infrastructure causes the defect or failure of the other. This fact contributes to the criticality of the system, called in the following case as the critical infrastructure that is the set of subsystems. Therefore, it does not suffice to ensure the safe subsystems separately, but instead it is necessary to systemically ensure the whole set of subsystems, which in practice means to search for the solution to a problem called the systems system safety (Prochazkova, 2008).

The reality is that each partial infrastructure and the whole set of such infrastructures is a complex dynamic system with a given level of adaptability. For ensuring its stability and functionality the threshold value must be known – the criticality that determines the condition at which the system does not ensure expected functions within a required time, a site, and in a required quality. The criticality of each partial infrastructure can be approached from two viewpoints, teleological and systemic (Eda, 2005):

1. From the teleological viewpoint it follows that the criticality is a result of the role and function of partial infrastructure in the society. This concept enables one to work with non-network and non-technical objects and processes.
2. Partial infrastructure criticality from the systemic viewpoint is a result of its position in the system or of its link to another partial infrastructure.

From both approaches it follows that the partial infrastructure criticality also influences the system that is a social partial infrastructure created by public administration, business subjects, educational and research institutions, and civic clubs.

Adopting the findings from the systems' system safety management (Prochazkova, 2010) the set of partial infrastructures in a region is a critical one if it is only capable of ensuring activities at which the only assurance is human survival in the region. For this purpose the analyses of sectors to which individual partial infrastructure belong have been performed in the world and they have followed the dependences among sectors, and the safety management that respect both the conditions for the functionality of individual partial infrastructures and the conditions for the functionality of a set of infrastructures; aggregated (critical) infrastructure. The term "criticality" was first used in connection with the nuclear reaction, where it denoted the threshold after which the spontaneous chain reaction followed. In connection with partial infrastructures and with critical infrastructure (the set of infrastructures) the criticality is, according to sources given in (Prochazkova, 2008), most competently expressed by the following definitions:

1. Criticality is a relative measure of impacts of frequently occurring defects and failures.
2. Criticality is expressed by conditions that describe a transition between quality changing conditions.
3. Criticality is a condition of extensive urgency.

From the given criticality definitions it is possible to derive that criticality is a threshold value that may be designed and that can relate to an event, process / function parameter, type of defects and/or resistance.

The determination of criticality is consistently related to the size of impacts caused by loss of the functionality of each infrastructure in the society. For criticality determination the following must be considered:

1. Concentration of humans and assets (protected interests).

2. Sectors of economy (sector analysis).

3. Types of mutual dependences among the partial infrastructures / sectors:
   i. On which item the assets of a given sector are dependent?
   ii. What is the mutual dependence of assets among sectors?

4. Types of services for the public:
   i. How long has the renovation of services furnishing taken?
   ii. Which compensation / substitutes can be accessible and available?

5. Public confidence in the public administration institutions:
   i. Can the defect of assets / public services result in a drop in the morale of citizens, a loss of national prestige, panic, rebellion, or civic disorder?
   ii. Can the defect of assets induce some impact / changes in the environment?

The determination of criticality in the service of territory can include the hazard assessment for disasters possible in a given region, considering the vulnerability of partial infrastructures in a given region, the mutual interconnections of partial infrastructures in a given region, i.e., theoretically the same principle as in the analysis and assessment of risks in a region, at which several protected interests are considered.

Therefore, the criticality determination process is the following:

1. Characteristics of assets (protected interests that are considered physical, cyber and human assets).
2. Determination of criticality (hazard analysis and consideration of the assets vulnerability in a site).
3. Assessment of impact on assets (concentration of humans and assets, economic impact, mutual dependences, reliability).
4. Assessment of consequences of losses, victims, damages and harm to assets.
5. Determination of priorities according to the given rules.

Analysis of data in literature, provided in the list and summarised in the works (Prochazkova, 2007b, 2008), showed that most of the procedures correspond to the above-mentioned general procedure, and the criticality is mostly determined by scoring, i.e., with a decision making matrix (Highway, 2002).

The interpretation of results for a given infrastructure (or for a set of infrastructures) is derived from the site position the coordinates of which form an obtained value of service measure (indeed measures of importance for a region) and measures of vulnerability. If it belongs to the sector:

- "high vulnerability and high importance of service" the condition of the infrastructure / technology / set of infrastructures is precarious, i.e., critical for a given region and from the viewpoint of security and sustainable development the situation must be solved through back up and enhancement of the given infrastructure,

- "lower vulnerability and lower importance of service" the condition of infrastructure / technology / set of infrastructures is satisfactory and it is necessary from time to time to perform a check-up of conditions in a given region,

- "high vulnerability and lower importance of service" the condition of infrastructure / technology / set of infrastructures is conditionally satisfactory and it is necessary to ensure preparedness for a sophisticated response in the case of infrastructure / technology / set of infrastructures failure and prevention to concentrate on preventive and mitigation measures leading to the reduction of infrastructure / technology / set of infrastructures vulnerability against possible disasters that can cause the failure,

- "lower vulnerability and high importance of service" the condition of the infrastructure / technology /set of infrastructures is conditionally satisfactory and it is necessary to ensure the preparedness for a sophisticated response in the case of infrastructure / technology / set of infrastructures failure and the prevention to concentrate on a reduction of the criticality of the infrastructure / technology / set of infrastructures in a region or to build redundancies of being objects of infrastructure / technology / set of infrastructures.

It is true that above-described procedure shows that the assessment of infrastructure / technology / set of infrastructures according to two criteria, namely the measurement of vulnerability and measurement of the importance of the service in a region is not a result of an objective computation of process analysis but rather the result of subjective estimations which is only tolerable in the case of the determination of a basic frame. The determination of criticality for some processes can be more complex.

When scoring the vulnerability and importance of a service it is necessary, in harmony with the work (Highway, 2002), to consider the following items:

- duration of renovation of infrastructures and technologies,
- impact of failure of infrastructures and technologies on human lives and security,
- caused detriment, harm and loses,
- impacts on environment,
- induced adverse interest.

From the viewpoint of human system safety (i.e., the security and sustainable development of human society) it is necessary to ensure the quality services in a region that are conditioned by the operational dependability of the critical infrastructure, understood as the systems system.

3 PROPERTIES INFLUENCING THE DEPENDABILITY OF PARTIAL INFRASTRUCTURES AND OF CRITICAL INFRASTRUCTURE

The dependability of partial infrastructures, and also a critical infrastructure, is the element that humans can influence. System dependability means that the system fulfils the given demands and its operation satisfies the given conditions. This aggregate property is not very practical for analytic purposes, and, therefore, it is broken down into two basic properties, as the vulnerability and the resistance are in the sense of the resilience. The following dependences are in force:

Vulnerability* = *f *(exposure, perception / sensitivity)*
Vulnerability* = *f *(sensitivity, dependability, life cycle)*
Resilience* = *f *(life cycle, ensuring, functional capability, operational readiness, adoption capacity)*

To reach a given level of dependability of partial infrastructures and a critical infrastructure both following points must be considered- the vulnerabilities against possible disasters (in the case of critical infrastructure including interdependences induced by mutual interconnections) and the human capabilities and opportunities to ensure a certain resilience. It is necessary to understand that the resilience is a certain functional capability of critical infrastructure to fulfil the tasks also during abnormal and critical conditions. To reach this condition it is necessary that critical infrastructure might attain a certain adoption capacity.

The dependability is a designed property and it is related not only to normal conditions, but also to abnormal and critical conditions at which, through the adoption capacity of critical infrastructure or critical technology, ensures the required reactions also during certain types of critical conditions. Usually, the critical conditions expected are considered in the sitting, designing, building, and operating of the infrastructure or technology, i.e., the foreseeable impacts which would be highly unacceptable (i.e., it is considered the precaution principle). Nevertheless, would be critical conditions could happen that are either unforeseeable or the result of a relevant fault of the operator and these can pass to inconvenient / unacceptable conditions, i.e., crisis conditions (Prochazkova, 2008).

The crisis potential can be expressed as a contemporary action of a trigger factor (trigger factors) and of non-steady conditions of a critical infrastructure setting, i.e.:

Crisis potential = trigger factors * non-steady conditions of setting

Likewise at the risk there is evaluated the occurrence probability, so also at crisis potential it is evaluated the crisis condition occurrence probability, namely including the assessment of impacts that are mentioned as the relevant disruption of functions of elements and processes of the critical infrastructure.

From the dependability it follows that the critical infrastructure, the system which plays a key role in a society, as it affects the decision making cycle of public administration and political and social solidarity, and supports the removal of physical and psychological harms, is very complex, and thus vulnerable. Therefore, in assessment three basic properties of critical infrastructure could be described and characterised, namely: resilience; vulnerability; and adoption capacity.

For the reason that today starts to approach the critical infrastructure as a complex socially-technological system (including mass flows, energy flows, information flows and reverse links including recycling) in the frame of societal metabolism, so the following definitions are:

1. *Resilience:*

Resilience is the capability of a system to adsorb and to use the deviations and changes so that it lives through them without the chance that quality changes of its structure might originate (Holling, 1973).
Resilience is a measure of such an extent of deviations that the system may absorb before the transition from one condition to another (Gunderson & Holling, 2002).
Resilience is a measure of a system's return rate to the balance condition (Gunderson & Holling, 2002).
Resilience is an extent of deviations that a system may absorb without a change to its stability (Gunderson & Holling, 2002).
Resilience determines the reactions remaining in a system and it is a measure of a system's capability to absorb condition changes (Franklin & Downing, 2004).
Resilience is a measure of the rate of a system's recovery from deviations (Adger, 2000).

2. *Vulnerability:*

Vulnerability is expressed as a relation between the exposure to hazard from an external activity and the capability of risk reduction in a certain time (Langeweg & Espeleta 2001).
Vulnerability is a measure of experiences of a system, subsystem or an element with damages that may occur with exposure to harmful phenomenon that induces a stressor (disaster) or deviation (Science, 2000).
Vulnerability expresses a measure between the system exposure to unforeseen phenomena and the load and the difficulty that is connected with their defeating (Chambers, 1990).
Vulnerability expresses a system capability of reacting to the occurrence of a harmful unfavourable event (Watts & Bohle, 1993).
Vulnerability is a result of a combination of exposure, resistance and elasticity (Dow, 1991).

3. *Adaptation:*

Adaptation is related to an unplanned reactive response to events or to conditions with the aim to avoid the unacceptable impacts through anticipating reactions (Glantz, 1992).
Adaptation includes changes in a system as a result of reaction to the manifestation of external forces or deviations (Smithers & Smit, 1997).

For designing the infrastructures and technologies we have been solving up to now the problem of safety of individual infrastructures, i.e., individual subsystems. From the present viewpoint before us there are minimally two following tasks:

1. To solve the problem of safety (including the functionality) of a set of mutually interconnected (dependent) infrastructures (i.e., systems system) for normal, abnormal and critical conditions.

2. To find the systems system critical conditions that are foreseeable or are a consequence of a significant mistake of the operator, and that under certain conditions can pass to high unfavourable and high unacceptable conditions, i.e., into the condition at which alone the human being is threatened which we usually denote as a crisis.

Therefore, we must today judge the critical infrastructure resilience, vulnerability and adaptation capacity considering that:

- *critical infrastructure resilience* is a measure of the critical infrastructure to absorb the changes of condition caused by a possible disaster (including the possible interactions),
- *critical infrastructure vulnerability* is a measure of a critical infrastructure's inability to react to a possible disaster (including the interactions) occurrence,
- *critical infrastructure adaptation* is a measure of a critical infrastructure capability to modify the structure of elements, links and flows of critical infrastructure in a way that the impacts of a disaster (including the interactions) are not unacceptable for the critical infrastructure.

4 CRITICAL INFRASTRUCTURE SAFETY

In the above-mentioned safety concept the critical infrastructure safety is a set of measures and activities that, when considering the critical infrastructure nature (systems system) and all possible risks and threats that are directed to ensuring the safety of elements, links and flows by way in order that their failure might not happen. In the situation of international dependence and the interconnection of sectors, the failure of the critical infrastructure in one country can affect more countries, and therefore, for critical infrastructure safety (inherently including the critical infrastructure protection) the following are both required - the sharing of responsibilities with the private sector and the exchange of information between the public administration and other relevant organisations; and secondly international co-operation (Prochazkova, 2007b). For ensuring critical infrastructure safety the following are used:

- special solutions in the land-use planning, sitting, designing, building, operating, maintenance, repair, upgrading, renovation, procedure changes, and for putting out of operation – here the concept of security strategists is used, namely emergency situations are always considered; they are not extraordinary, and, therefore, for the critical infrastructure safety support measures and activities are implemented, see protection and security systems specially distributed in a site and backed up (today with redundancy of up to 4 x 100%),
- continuity plans for ensuring the critical infrastructure's survival during possible emergency situations – here the concept of security strategists is used, namely emergency situations are considered; they are not extra-ordinary, and, therefore, for the critical infra-structure safety support certain measures and activities are implemented that ensure the conservation of minimal functionality of critical infrastructure and the perspective for the future, that after the emergency situation's stabilisation it would be possible to start and to restore the whole extent of the critical infrastructure's operation,
- crisis plan for the case in which all or most of the security countermeasures fail owing to an extreme disaster size, or owing to an unforeseen combination of random phenomena that intensify disaster impacts.

The critical infrastructure systems are multiplex owing to their nature and the conditions of functionality in the human system. Therefore, the critical infrastructure safety problems (inherently including the critical infrastructure protection problems) are multidisciplinary and interdisciplinary, namely in technical, managerial, and organisational domains on different levels - legal, financial, personal, knowledge, international, etc. For the solution of problems of critical infrastructure safety it is necessary to understand the targets and roles of critical infrastructure in the human system. The process model ensuring critical infrastructure safety is based on the method of safety engineering (ESRIF, 2009). All relevant disasters are assessed – the so-called "all hazard approach" (FEMA, 1996). In order that the problem might be understandable and transparent it is necessary to use further ranking of the primary disasters: technological accidents (internal) of critical elements, links and flows in the critical infrastructure system. It is necessary to take into account material defects, aging, insufficient maintenance etc.; errors or failures of control systems; human errors; natural disasters or technological accidents (external) of other systems; and terrorist attacks, criminal acts or war.

In the theoretical domain it means the delimitation of integral risk and its partial components, with regard to protected interests (assets) and possible disasters in a given region and the specification of measures and activities leading to an increase in a region's safety in the real world; it is not expected to ideally solve technological problem but to be for the protection, conservation, and development of basic protected interests, i.e., an optimal interconnection of measures directed towards human lives and security. The basic strategic approach for critical infrastructure safety is: nothing is absolutely safe; and elements and networks of critical infrastructure can fail sooner or later, and, therefore, it is necessary to establish sophisticated regional safety management. Effective and efficient safety management must be supported by present knowledge and on the right assessment in a context that is valid for a given region. Therefore, the basic role belongs to the research that at present solves:

- impacts of interdependences among the critical infrastructure subsystems and the human system subsystems on the systems system safety,
- procedures and targets for ensuring the critical infrastructure safety from a managerial view on the level of state,
- possible distribution of tasks in the critical infrastructure safety management between the public and private sectors (it goes out of risks in a region with the aim of reaching an optimal position for the public and private sector),
- requirements on the personnel of the critical infrastructure and technology owners,
- tasks of security components at defeating the emergency situations, induced by the extensive,
- outage of the critical infrastructure,
- general frame for critical infrastructure safety.

Methodology for the critical infrastructure safety management (inherently containing the critical infrastructure protection) relies on keeping the further given procedure (ESRIF, 2009, Prochazkova, 2007b, 2010), i.e., the management:

- is always directed to essential aspects,
- considers that the development must be sustainable and far-sighted (i.e., there must be balance between the economy, environment and social domain) and the primary target is the reduction of vulnerability,
- pays attention to the aspects that are the most vulnerable,
- ends emergency situations and when doing so it is directed to the needs and priorities
- regarding the basic priorities of human protection and the protection of critical sources and systems on which the community's existence depends,
- supports a prevention culture, programmes for the prevention and the preparedness to defeat emergency situations and it insures that these items are included in the territory development programme,

- ensures that the citizens have right to just aid (remedial service) and that the aid is dispensed fairly and consistently without regard to economic or social circumstances and territorial location,
- ensures that citizens are included in the response management system not only as potential victims,
- ensures that citizens know emergency plans, content of plan of response to disasters, way to react and to be able to justify the origination of an emergency situation, etc.
- ensures that the emergency management system is also transparent for citizens and it is adjusted to the local conditions,
- ensures that the emergency management system is legitimate and acceptable and that it is based on a systemic approach,
- ensures that critical infrastructure safety (inherently including the critical infrastructure protection) is the matter of both the private sector and the public sector.

For decision support system profiting the continuity of critical infrastructure at renovation of property in a territory affected by a disaster is quite a basic concept for the determination of critical elements, critical processes, critical functions, critical infrastructures and critical technologies in a region. This concept relies on the risk analysis methodology and on actual terms of safety management in a region. It is possible to summarise that this process is determined by:

- way of assessment (acceptation) of risk, judgement and governance of risk,
- methodology of risk analysis and operation research,
- tools of safety management including tools of crisis management,
- specific particularities of cyber infrastructure,
- threat of conventional and unconventional terrorism,
- way of determination of priorities of system vulnerability,
- population awareness and properties of post-modern society.

The reasons why the critical elements, critical processes, critical functions, critical infrastructures and critical technologies in the region are determined are given by the demand of the reduction of risks in the human system from the view of its safety and development in the broadest sense. It is a matter of the reduction of vulnerability (resilience increase) of key elements of the human system that are basic for society being at all levels of organisation and state administration, ensuring the functionality of life-giving systems and the rational protection of critical infrastructure (Prochazkova, 2007b,2010).

5 PRINCIPLES FOR CRITICAL INFRASTRUCTURE SAFETY MANAGEMENT

Regarding the above-given facts it is necessary to take into account that we can ensure the safe critical infrastructure in two ways. The first one is more or less ideal and it consists of the construction of critical infrastructure on a “green field”, i.e., from the beginning we create safe systems system (each partial infrastructure is also resistant to the failure of the others). The other, more realistic, way consists of an application of site specific measures ensuring the inherent mitigation of impacts of each individual infrastructure failure on the other parts of critical infrastructure; e.g., the others start independently to work in an insular regime.

In practice the failure of critical infrastructure often comes from so-called internal causes. Therefore, it is necessary to consider the technical level, conditions, and durability of a given infrastructure (35 – 40 years; max. 50 years), and the reality that through this time interval the ability for a return on investment must be ensured and that human security must not be threatened. The longer the time interval for which the infrastructure performance is planned, the more modern (timeless) solution must be used. Each variant must be financially acceptable and must also be acceptable from the viewpoint of accessible technologies and of qualified human sources. For decision making on infrastructure renovation it is necessary to consider expenses and their return ability. Usually a criterion is used that says “when expenses for infrastructure renovation do not return, e.g., after natural disaster within 10 years, it is better to build a new one”. From the public interest viewpoint it is necessary to remove or to limit the interventions of politics into decision making on the infrastructure in the territory because their targets are usually different to the long-term safety, including the functionality and reliability of the infrastructure in the region without regard to the political party in power.

In the frame of ensuring human system security and sustainable development it is permanently necessary to perform measures that reduce the infrastructure criticality in a region. By building the new infrastructure it is necessary to ensure the suitable number and regional distribution of objects of important infrastructure that are sufficiently resistant to the expected disasters in a given region, and through that to systematically reduce infrastructure criticality.

Expenses for critical infrastructure are not only the costs for its design and building, but they also include the costs for its operation, maintenance, repair and modernisation. Therefore, the risks connected with each infrastructure must also include the risks from just given domains and the region management must know how to deal with them. It is necessary to assess the risks from disasters that can be denoted as financial market failures because of the connected failure of finances for the maintenance, operation, repair and modernisation of objects of critical infrastructure. This is caused by the fact that critical infrastructure criticality increases if no good maintenance and good repair are performed (which causes the vulnerability to increase).

Since nothing is perfect, a plan for renovating infrastructure, especially for critical situations, needs to be prepared. This plan must be proactive, properly assessed; it must contain transparently managed risks and answers to questions such as: what to do?, how to do it?, in which time interval?, do risks for other protected interests increase? etc. Because the critical infrastructure is a set of mutually connected (i.e., dependent) infrastructures it is necessary to pay great attention to the study of internal dependences, because analogies based on the study of simple technological systems indicate that for critical infrastructure failure there are much more important links and flows that mutually interconnect subsystems.

6 CONCLUSIONS

The critical infrastructure safety is a basic problem of the present days. The problem today is very broad as we must solve, not only individual infrastructure securities that depend on the technical aspects of individual infrastructures and on respecting human factors, but also aspects connected with the safety, dependability and functionality of a set of individual infrastructures in a given territory from the viewpoint that the critical infrastructure is protected against internal and external disasters and simultaneously does not threaten its vicinity (humans, environment, and property) and correctly fulfils the expected functions for the territory. At present we try to find a solution that also enables human survival in a territory during catastrophes. For this case the paper summarized the principals for critical infrastructure safety management. The conclusions were verified for electric infrastructure and now collected data exist for the judgement of transport infrastructure and for its integration into regional critical infrastructure, as, from the reasons given above, many of critical infrastructure problems are site specific.

7 REFERENCES

Adger, N.W., 2000. *Social and ecological resilience*. Progress in Human Geography 24, (2000) No 3.

Chambers, R., 1990. *Vulnerability, coping and policy*. IDS Bulletin. 20, No. 2.

Dow, K., 1991. *Exploring differences in our commnon future*. Geoforum 23, No. 3.

Eda, 2005. *Workshop on critical infrastructure protection and civil emergency planning-dependable structures, cybersecurity, common standard*. Zurich 2005, Centre for International Security Policy, www.eda.admin.ch

ESRIF, 2009: *ESRIF Final Report*. EU, Brussels 2009, 311p.

FEMA, 1996. *Guide for all-hazard emergency operations planning*. State and Local Guide (SLG) 101.

Franklin, S. &. Downing, T., 2004. *Resilience and vulnerability*, GECAFS Project, Stockholm Environment Institute.

Glantz, M., 1992. *Global warming and environmental change*. Global Environmental Change. 2.

Gunderson, L. & Holling, C. S., 2002. *Panarchy: understanding transformation in human and natural systems*. Washington, Island Press.

Highway, 2002. *A Guide to highway vulnerability assessment for critical asset identification and protection*. National Cooperative Highway Research Program Project 20-07/Task 151B, Science Applications International Corporation–Transportation Policy and Analysis Center, Vienna.

Holling, C.S., 1973. *Resilience and stability of ecosystem*. Annual Review of Ecology and Systematics, 4, No 1.

Langeweg, F. & Espeleta, E. E., 2001. *Human security and vulnerability in a scenario context*. HDP Update 2.

Moteff, J., Copeland, C. & Fischer, J., 2003. *Critical infrastructures: what makes an infrastrucuture critical*. Report for Congress, 2003, CRS Web, Order Code RL31556.

Prochazkova, D., 2007a. *Strategy of safety and sustainable development management of territory* (in Czech). ISBN 978-80-7251-243-0, PA ČR, Praha, 203p.

Prochazkova, D., 2007b. *Problem of critical infrastructure protection* (in Czech). Indikace a reflexe rizik společenské praxe jako teoretický základ pro rozvoj policejních sluțeb. PA ČR v Praze, Praha, ISBN 80-7251-229-3, 219-245.

Prochazkova, D., 2008. *Critical infrastructure safety from the viewpoint of systems system* (in Czech). Riešenie krízových situácií v špecifickom prostredí. ISBN 978-80-8070-846-7, FŠI ȚU, Țilina 2008, 605-610.

Prochazkova, D., 2010. *Critical infrastructure and principals for its safety* (in Czech). Manațérstv o țivotného prostredia. ISBN 978-80-89281-34-3, Strix et VeV, Țilina 2010. 301-366.

Science, 2002. *Framework for vulnerability analysis in sustainability science*. Proceeding of National Academy of Science 100 (14).

Smithers, J. & Smit, B., 1997. *Human adaptation to climatic variability and change*. Global Environmental Change 7 (2).

Stein, W., Hammerli, B, Pohl, H. & Posch, R. (eds), 2003. *Critical infrastructure protection – status and perspectives*. Workshop on CIP, Frankfurt am Main, www.informatik2003.de

Watts, J.M. & Bohle, G.H., 1993. *The Space of Vulnerability*. Progress in Human Geography 17, No. 1.

Abdominal Finite Element Model for Traffic Accidents Injury Analysis

L. Ondoková* & L. Hynčík
Research Center New Technologies, University of West Bohemia, Plzeň, Czech Republic
** Corresponding author: cihalin@ntc.zcu.cz*

DOI: 10.2478/v10158-010-0023-z

ABSTRACT: The abdominal cavity is a vulnerable region of the human body. The severe and critical abdominal injuries arising during traffic accidents are the second most important bodily injuries after thoracic injuries. The injuries are predominantly caused by contact with the lap belt, steering wheel, armrest, dashboard, side door, etc. However in terms of investigating the biomechanical response of the abdomen, experimental studies have turned out to be particularly difficult to perform and the results obtained are not easy to interpret. Therefore attention should be paid to a generation of more realistic human body models with detailed inner organ models in order to be able to describe the organ injury mechanisms during accidents. In this study the abdominal finite element (FE) model was created to improve the abdominal part of the human body model ROBBY. This should ensure the ability of an updated model ROBBY to predict the abdominal injury during various impact conditions. The abdominal model geometry was created on the basis of real anatomical human data. Tissue characteristics completing the organ geometry were obtained from public sources. The created abdominal model was consequently scaled and embedded into the ROBBY model representing a 50th percentile male. The updated ROBBY model was validated with a comparison of the simulation results during abdominal oblique impactor tests and abdominal frontal rigid bar tests with available cadaver experimental results. It was found that the updated ROBBY model with the new deformable abdominal model is able to predict the response of the human abdomen during various impact conditions very well. Moreover due to the precision of the abdominal model the injury of individual abdominal organs can be predicted during impact. This allows the simulation of real vehicle accidents and the assessment of human abdomen injuries arising during accident to be performed.

KEY WORDS: Biomechanical model, human abdomen, generation, validation, injury assessment.

1 INTRODUCTION

With development of computers and numerical methods during the last years, more complex virtual biomechanical models have been developed to study human body injury mechanisms in vehicular impacts (Haug et al., 2004; Iwamoto et al., 2002; Oshita et al., 2002; Ruan, 2005, and Zhao & Narwani, etc.). These models of various complexity show promise as useful tools for the better understanding of impact problems and therefore may reduce the dependence on cadaver experiments, which are expensive, time consuming, hard to repeat, etc. Moreover, the great advantage of a well validated deformable human model is the ability to predict the injuries to inner organs.

In the presented study a new abdominal FE deformable model was generated. The abdominal model was implemented into the human articulated rigid body model ROBBY (Hynčík, 1998), which was previously developed at University of West Bohemia in cooperation with ESI Group (Engineering Simulation for Industry).

ROBBY, which represents a model of the average adult man, is still being improved to obtain a more factual human body model with the possibility to predict organ injuries during vehicle accidents. This model belongs to the ROBBY family, which consists of ROBBY – a model of a 50th percentile male (on various levels (deformable, rigid)), ROBINA – model of a 5th percentile female and BOBBY – a model of a child. The first ROBBY model was created from rigid bodies only connected with joints (Hynčík, 1998). Consequently, muscles and some internal organs were integrated into ROBBY (Hynčík, 1998; Hynčík, 2002). Recently, a new FE deformable thoracic model based on real anatomical human data was created (Číhalová, 2006) and integrated into the ROBBY model (Číhalová & Hynčík, 2008). The aim of the presented study was to continue with the updating of ROBBY model to create a more realistic human body model with the possibility to predict organ injuries during accidents.

2 METHODS

The abdominal model generation (geometry creation, material and contact definition) and the investigation of its dynamical response during various impact conditions are described below.

2.1 The creation of abdominal organ geometry

The geometry arrangement of the new abdominal FE model was based on real anatomical human data. The photographs of cross-sections through the human body offered by VHP (Visible Human Project®, 2003) were used to construct the geometry arrangement of individual abdominal organs. These photographs were processed in advanced software for their visualization, Amira® (2002), which is able to create a 3D object model from the cross-sections through this object. In this software the boundaries of individual organs were marked in each photograph. Consequently, the tetrahedral meshes of individual abdominal organs were generated. The meshes were remeshed to the hexahedral ones in the Altair® HyperMesh® (2009) software, high-performance finite element pre- and post- processor for popular finite element solvers. The measurements of the individual elements representing the abdominal organs were chosen with respect to the stability of computation in the solver PAM − CRASH™ (2009).

The time step was held not to be smaller than 10^{-3} ms. The created abdominal organ models were scaled in accordance to anatomical reality (Gray, 1995). Consequently, the scaled abdominal model was integrated into the ROBBY model (Figure 1).

Figure 1: The thoracic and newly created abdominal segments of the ROBBY model.

Great attention was paid to the liver organ, which is a vital organ (production of bile, blood formation, manufacturing of anticlotting heparin, storage of proteins and sugar). This organ is very often injured during accidents. Since the liver is thickly interlaced by bloodvessels, the models of the inferior vena cava and portal vena were created on the basis of VHP photographs (Visible Human Project®, 2003) and anatomy (Gray, 1995). These were consequently integrated into the liver model (Figure 2).

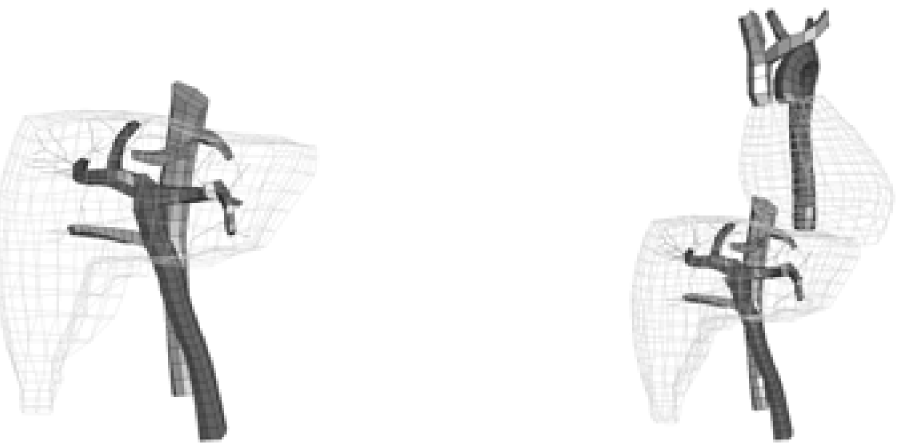

Figure 2: The blood vessels model inside the liver and its connection to the heart.

To define the correct linkage of blood vessels inside the liver, a grid of insignificant mass within the liver was generated. The vessel models were fixed by a tied contact offered by PAM−CRASH™ (2009) to this grid. Moreover, the vena cava was connected to the heart (Figure 2) according to anatomical reality (Gray, 1995).

2.2 Description of the abdominal model

The models of abdominal organs, such as the liver with the portal vena and the inferior vena cava, the spleen, the left and right kidney, intestines, and the stomach, were embedded into the new abdominal model. The urinary bladder was used from the previous ROBBY model. The thoracic and abdominal segments were separated by the diaphragm model. Some of the abdominal organs were located in the peritoneum model. The solid organs, such as the liver, spleen and kidneys, were modeled with a set of brick elements described by linear visco-elastic behavior (PAM-CRASH™, 2009). The hollow organs, such as the stomach and intestines, were simulated in two ways: i) by a set of brick elements described by linear visco-elastic behavior and ii) by a biobag (bag with the fluid inside) (Hynčík, 2002). One integration point scheme with viscous method prevention was used for solid elements (PAM-CRASH™, 2009). The reason for the use of the one point integration scheme was a four times lower time costliness in comparison to the eight integration point rule (PAM-CRASH™, 2009).

The biobag model derived from the airbag model (Haug et al., 2004) can be used in the FE modeling of organs. Its big advantage is the saving of computational time, since there are no finite elements describing the fluid inside. The fluid has only its state characteristics, which is constant in the whole volume surrounded by the biobag surface.

Constant atmospheric pressure and constant normal body temperature were applied to initialize the biobag. The isothermic process was supposed, since there is no considerable change of temperature in the human body. The material characteristics of the fluids inside the biobags were obtained in cooperation with the ESI Group.

All abdominal organs were covered by thin layers represented by the set of shell elements. One integration point scheme with stiffness method prevention (PAM-CRASH™, 2009) was used. The reason for the use of the one point integration scheme was a 2.5 times lower time costliness in comparison to the four integration scheme use.

The linear elastic isotropic material model offered by PAM−CRASH™ (2009) was used to capture the behavior of abdominal organ layers and of the peritoneum and diaphragm.

Two types of contacts offered by the solver PAM-CRASH™ were used to simulate the mutual contacts of all abdominal organs. The first type of used contact is the sliding contact (PAM-CRASH™, 2009). This contact allows two interfaces to slide with respect to each other. The second one is the tied contact (PAM-CRASH™, 2009), where one part is fixed at a certain distance (describing the reality) with respect to a second one. This contact is used to simulate ligaments or firm connections among organs. Particular examples of such contact in the abdominal model are the simulation of the close conjunction of the liver to the diaphragm or for fixation of blood vessels inside the liver.

2.3 Validation of the abdominal model

The updated model ROBBY, i.e., the ROBBY model with the new abdominal model, was validated against a pendulum impactor test according to Viano (1989) and Viano et al. (1989) (Figure 3) and a rigid bar test according to Cavanaugh et al. (1986) (Figure 3). These two tests approximate the most common situations during a traffic accident in laboratory conditions. The first one approximates the oblique impact, when the upper abdomen comes to contact with side door. The second one approximates the frontal impact, when the lower abdomen comes into contact with the bottom part of the steering wheel. The validation results of simulations were compared with cadaver experimental data according to Cavanaugh et al. (1986), Viano (1989) and Viano et al. (1989). In both test types, the solid and biobag variants to model hollow abdominal organs were used.

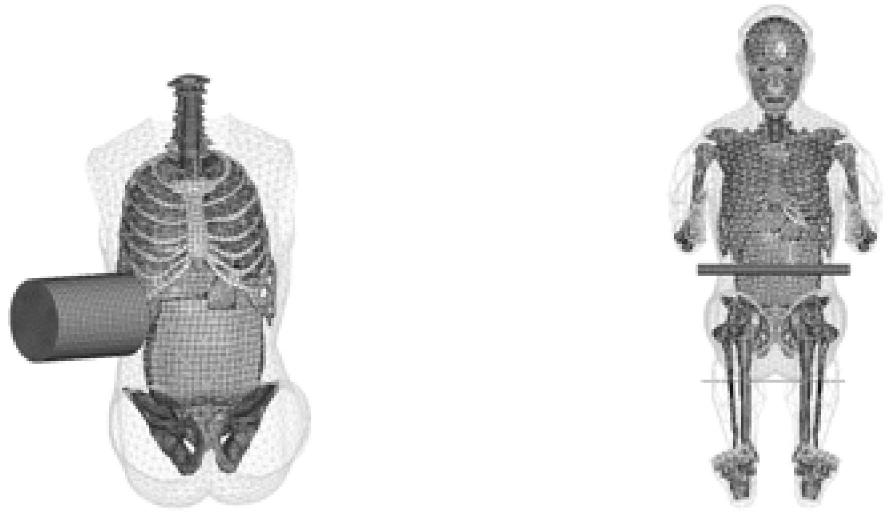

Figure 3: Initial position of the ROBBY model in the pendulum impactor test according to Viano and in the rigid bar test according to Cavanaugh.

2.3.1 Model validation against Viano test

Data of cadaver studies presented by Viano (1989) and Viano et al. (1989) were used to validate the upper part of the abdominal model in the oblique direction.

Two tests with various initial conditions: i) Impactor of mass 23.4 kg impacting the abdomen at speed 4.79 m s^{-1} and ii) Impactor of mass 23.4 kg impacting the abdomen at speed 8.32 m s^{-1}, were performed.

The force-deflection dependencies were investigated and these were compared with the experimental results (Viano, 1989; Viano et al., 1989). The force value was taken as the impactor force (Haug et al., 2004) in the impact direction (Viano, 1989). The force was filtered by Channel Frequency Class (CFC) 600 (PAM-CRASH™, 2009). The abdominal deflection was considered to be the difference of total displacement of the impactor and thoracic vertebrae T12 (Viano, 1989), i.e., displacements in all three directions were taken into account.

2.3.2 Model validation against Cavanaugh test

Data of cadaver studies presented in Cavanaugh et al. (1986) were used to validate the lower part of abdominal model in the anterior-posterior direction.

Two impacts were performed with various initial conditions: i) low energy impact (Impactor of mass 32 kg impacting the abdomen at speed 6.1 m s^{-1}.) and ii) high energy impact (Impactor of mass 64 kg impacting the abdomen at speed 10.4 m s^{-1}.).

The force-deflection dependencies were investigated. The abdominal deflection was taken as the difference of horizontal displacement between the impactor and L3 (Cavanaugh et al., 1986). The force value was considered to be the impactor force in the impact direction (Haug et al., 2004). The force was filtered by CFC 600.

3 VALIDATION RESULTS

3.1 Validation results of Viano test

Figure 3 compares the simulation results of force-deflection dependencies of the abdominal model for both organ model variants with experimental results during right side impacts.

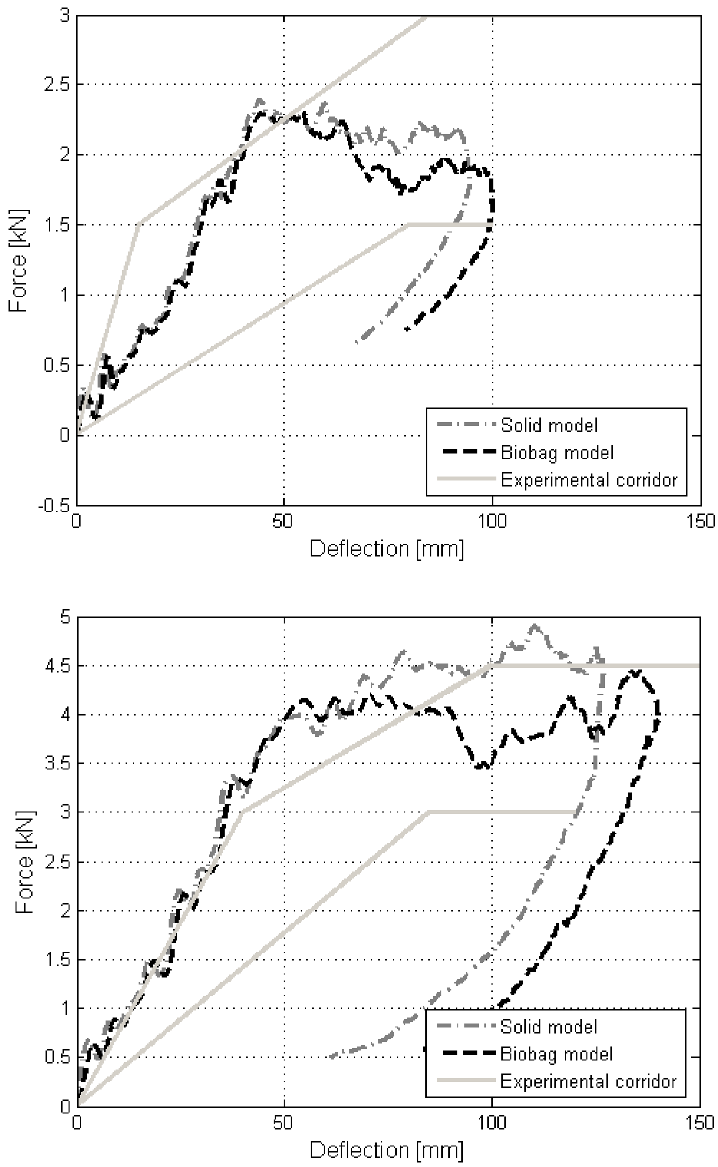

Figure 3: The validation results during the oblique impactor test at 4.79 m s^{-1} and at 8.32 m s^{-1}.

The force-deflection dependencies, which are hysteresis curves, are characterized by their loading, plateau and unloading part. The loading part is characterized by a rapid rise, which is mainly caused by the viscous behavior of the upper abdomen. The plateau region is also the result of the viscous response. The unloading part represents the unloading of the compressed tissues and the elastic non-linear unloading of the upper abdomen follows. The shape of these three phases depends on the impact energy.

For the impactor pendulum test at impact speed 4.79 m s^{-1} the simulation results for the solid and biobag model are comparable with the experimental results, i.e., the results of the simulations fit the experimental corridor. The impacted force predicted by the abdominal model reaches its maximum during the lower deflection in comparison with the experimental results (Figure 3). This shows the higher stiffness of the upper abdomen model in comparison with a real human abdomen. The stiffness could be reduced by selecting different organ material parameters. However, since the simulation results are comparable with experimental results and due to the lack of time, this can be the subject for future studies.

For the impactor pendulum test at the impact speed 8.32 m s^{-1} the simulation results for the solid and biobag model are comparable with the experimental ones in all three phases: phase of loading, plateau and unloading. The impactor force reaches its maximum during lower deflection in comparison with the experimental results, as well as during the 4.79 m s^{-1} Viano test (Figure 3).

3.2 Validation results of Cavanaugh test

The simulation and the experimental results of the low energy and high energy Cavanaugh test can be seen in Figure 4. The loading part of the experimental force-deflection curve of the lower abdomen of the human cadaver can be characterized by an almost linear rise from zero to peak force. The unloading part of the experimental force-deflection curve of the lower abdomen is the approximately vertical line (Cavanaugh et al., 1986).

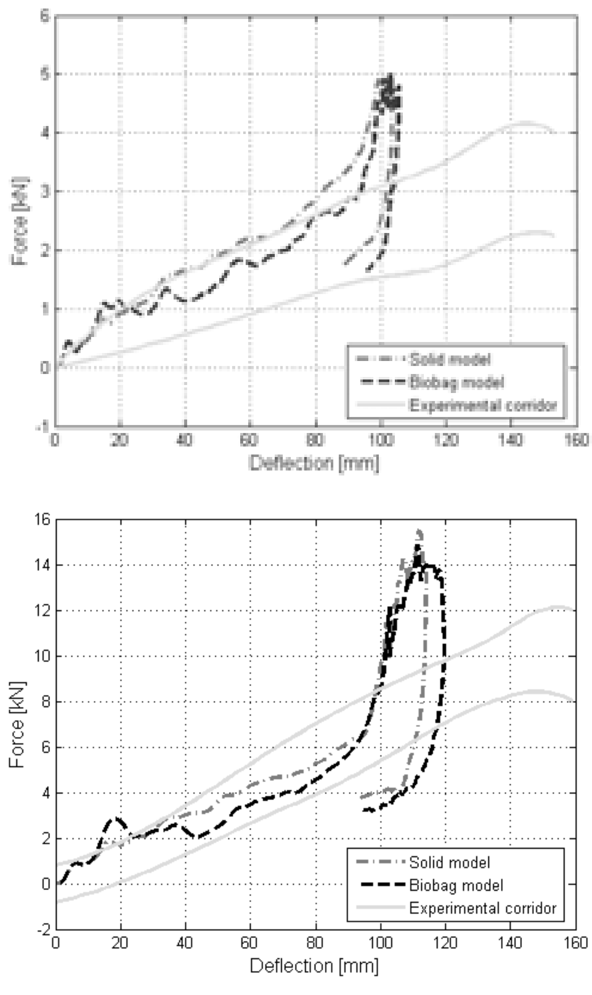

Figure 4: Results of validation during the frontal rigid bar test at 6.1 m s^{-1} and at 10.4 m s^{-1}.

In both rigid bar tests the results of the simulation are comparable with the experimental ones. In both cases there is a problem around deflection of approximately 90 mm, when the force increased rapidly.

In summary, the comparison of the simulation and experimental results for the lower and upper part of the abdomen shows that the created abdominal model is able to approximate the abdomen response of the cadaver sufficiently.

4 DISCUSSION

Computer numerical based simulations are presently frequently used to analyze the crash situation of a vehicle in detail. On the other hand the detailed analysis of passenger injuries is limited. This is caused by the fact that the numerical dummy models do not permit the study of inner organ injuries. The possibility arises of using FE human body models with integrated inner organ models. However, such human body models contend with the problem of obtaining parameters describing organ behavior and arising injuries.

Our department has been developing the FE human body model ROBBY for a long time. This model is still being improved in order to be able to describe various crash situations. In this study the new deformable model of abdomen was developed. The geometry of model was based on data offered by the VHP (Visible Human Project®, 2003). Material parameters completing the inner organ models were obtained from Ruan (2005); Ruan (2003) and Zhao & Narwani. The division of the abdominal organs into two groups: i) hollow organs and ii) solid organs was taken into account. To capture this reality, the modeling by a set of solid elements or by a biobag (sac with fluid characterized by state relation inside) was applied. The abdominal model was validated by a frontal rigid bar test at the lower abdomen part according to Cavanaugh et al. (1986) and by an oblique impactor test at the upper abdomen part according to Viano (1989) and Viano et al. (1989). Figures 3 and 4 summarize the results of the validation. It can be concluded that the newly created abdominal model was validated satisfactorily, i.e., the results of the simulations correspond to the experimental ones.

In the case of the Cavanaugh tests (Figure 4) an abrupt increase of force in the deflection of approximately 90 mm can be observed. This increase is at the moment when the compressed abdominal cavity starts to push on the lumbar spine. Hence the cause of the sudden growth is the greater stiffness of the lumbar spine. This problem was beyond the scope of this study. However, a new model of the lumbar spine, based on the real anatomical human data offered by VHP, will be created in the near future. This model will be completed by suitable material data and consequently it will be validated. It can be noted that the influence of the spine is not apparent in the case of the Viano test (Figure 3). This is caused by the fact that the abdomen deformation is smaller in the case of Viano test than in the case of the Cavanaugh test. This corresponds with the reality that there is no contact of the impactor with the ribcage in the case of the Cavanaugh test in comparison with the Viano test, i.e., a bigger deflection of the abdomen arises in comparison to the Viano test.

5 CONCLUSION

Dynamical abdominal responses during the frontal rigid bar test and the oblique pendulum test were investigated using the human body model ROBBY with a newly created abdominal model. The model was validated by a comparison of force-deflection dependencies obtained from simulations with experimental results. This validation is satisfactory. The abdominal model can be used to predict organ injuries during various accidents.

ACKNOWLEDGEMENTS

The study was supported by the John H. and Anny Bowles Foundation. Great thanks go to ESI Group International.

REFERENCES

Altair® HyperMesh® 7.0, Online:http://www.altair.com.

Amira®, Version 3.1, Users guide, 2002.

Cavanaugh, J. M.; Nyquist, G.W., Goldberg, S. J.; King, A. I.: Lower Abdominal Tolerance and Response, Proc. 30th Stapp Car Crash Conf., 1986, SAE 861878: 4163.

Číhalová, L.: Development of biomechanical deformable thoracic model, Journal Engineering mechanics, 13 (6): 453-465, 2006.

Číhalová, L.; Hynčík, L..: Human body finite element model as instrument for improvement of passive safety, In Journal Transactions on Transport Sciences, 1 (3): 109-116, 2008.

Číhalová, L..: Biomechanical models of tissue and their implementation into human body, Ph.D. thesis, University of West Bohemia, Plzeň, 2008.

Gray, H.: Gray's Anatomy, Churchill Livingstone, 1995.

Haug, E.; Choi, H. Y.; Robin, S.; Beaugonin, M.: Human models for Crash and Impact Simulation, Special Volume of Handbook of numerical analysis, vol. XII, Editor-P.G.Ciarlet, 2004, pp. 231-670.

Hynčík, L.: Numerical human model for crash test purposes, diploma thesis, Plzeň, 1998.

Hynčík, L.: Biomechanical model of abdominal organs and tissue for car crash test purposes, Ph.D. thesis, University of West Bohemia, Plzeň, 2002.

Iwamoto, M.; Kisanuaki, Y.; Watanabe, I.; Furusu, K.; Miki, K.; and Hasegava, J., Development of a finite element model of the total human body model for safety (THUMS) and application to injury reconstruction, Proceedings of IRCOBI Conference: 31-42, 2002.

Oshita, F.; Omori, K.; Nakahira, Y., Miki, K.: Development of a Finite Element Model of the Human Body, 7th International LS-Dyna Users Conference: 3-37, 2002.

PAM-CRASH™, Notes Manual, Version 2009.

Ruan, J.S.; El-Jewahri, R.; Barbat, S.; Prasad, P., Biomechanical analysis of human abdominal impact responses and injuries through finite element simulations of a full human body models, Stapp Car Crash Journal, 49: 343-366, 2005.

Ruan, J.; El-Jawahri, R.; Chai, L.; Barbat, S.; Prasad, P.: Prediction and Analysis of Human Thoracic Impact Responses and Injuries in Cadaver Impact Using a Full Human Body Finite Element Model, Stapp Car Crash Journal, 47: 299-321, 2003.

Schmitt, K.U.; Niederer, P.; Walz, F.: Trauma biomechanics, Introduction to accidental injury, Springer-Verlag, Berlin Heidelberg, New York, 2004.

Viano, D. C.: Biomechanical Responses and Injuries in Blunt Lateral Impact, Proc. 33rd Stapp Car Crash Conference. SAE 892432: 113-142, 1989.

Viano, D. C.; Lau, I. V.; Asbury, C.; King, A. I.; Begeman, P.: Biomechanics of the human chest, abdomen, and pelvis in lateral impact, Accid Anal, 21 (6): 553-574, 1989.

Visible Human Project®, U. S. National library of medicine, 2003, Online: http://www.nlm.nih.gov/research/visible/visiblehuman.html.

Zhao, J.; Narwani, G., Development of a human body finite element model for restraint system R& D applications, TAKATA - Automotive System Laboratory, Inc., paper number 05-0399.

The Synergy Transportation

V.Vlčková* & Z. Votruba

Both authors are with the Faculty of Transportation Sciences, Czech Technical University in Prague, Czech Republic
**Corresponding author: vlckova@fd.cvut.cz*

DOI: 10.2478/v10158-010-0024-y

ABSTRACT: Paper reflects the aspiration to denominate the relation between transportation and fields of environmental and nature phenomena, following and having respect for the principles of sustainable development. Systems knowledge and methodologies are used: Systems approach; methodologies of synergy and principles of sustainable development. The Theory of Production Function is extended to tackle these problems.

KEYWORDS: Transportation as a science, systems approach, synergy, sustainable development, production function.

1 INTRODUCTION TO THE TERNARY RELATION: TRANSPORTATION - HUMAN SOCIETY - SUSTAINABLE DEVELOPMENT

The primary factor of this study is the aspiration to denominate the relation between the branch of transportation & Environmental Sciences, following and having respect for the principles of Sustainable Development. A definition of this relation can consequently inspire a set of methodologies, methods, technologies, and techniques of transportation to be used and enhance their Problem Solving abilities. To reach this goal:

- firstly, the formulation of theses and the attributes of branch of transportation should be completed (Vlček, 1996),
- secondly a set of Systems Knowledge and methodologies are to be used (Systems approach; a body of knowledge on synergy) (Veselý, 2005; Vlček, 1984; Vlček, 1999; Vlček & Petr, 1983);
- tertio principles of sustainable development, influencing the perception of the application area of the branch of transportation, are to be taken into account (EC, 2003; Mezřický et al., 2005; Míchal, 1976; Míchal, 1994; ČR, 2004; ÚÚR, 2000).

The branch of transportation is in the role of the object of research. Systems Approach (Vlček, 1999), a set of tools of Systems Engineering and topics of studies of synergy are sets of methodologies used, while terminologies, methodic tools and the concept of sustainable development are perceived as an application environment, as peripheral surroundings of the process of this research. Transportation as a science is fundamentally analyzed in (Vlček, 1996). It is sketched out as a conceptual abstract base for the research of transportation features. A fulfillment of the four basic prerequisites of the concept of transportation science is completed with a primary sketch of the formalization of the basic effects of transportation -

Production Functions of Transportation (Vlček, 1999). The effects from the 1st to the 5th degree of formulated functions are explained. In (Vlček, 1996) presented set of considerations and argumentations, including pertinent terminology, is thoroughly used within this paper.

Besides the Systems Approach (Vlček, 1999), a set of tasks solving practices based on the body of Systems Engineering - see (Veselý, 2005; Vlček, 1984; Vlček, 1999; Vlček & Petr, 1983), is thoroughly utilized (for example for an efficient capture of external relationships and connections with the other branches and, consequently, with the whole of the anthropogenic sphere). The notion of sustainable development (as well as its terminology, methodology, semantics, environment i.a. described in (ČR, 2004)) at a relatively high rate conforms to the mechanisms and procedures of a Systems approach (Vlček, 1999) to the complex tasks' solutions. It is therefore possible to use it in a similar manner. Unifying three apparently unique branches - economy, environmental science, and social community responsibility – there is an aim to perceive and to implement for any tasks the relationships with the surroundings, and to respect feedback impacts as well. In other words – it is necessary to formulate and to solve any transportation task in the large scale with all significant connections. Thus it is also plausible to forestall projecting oversized or unnecessarily complicated transportation systems that have not adequately taken into account both the local and global consequences, the future of energy sources, and social impacts. This aspect of sustainability has de facto tight links with an old problem within the economy, i.e., an appropriate evaluation and a setting of externalities.

2 METHODOLOGICAL COMPONENTS

2.1. TRANSPORTATION AS A SCIENCE

In the object of transportation four degrees of production function are recognized (Vlček, 1996; Vlček, 1999).

The first degree of production function, E = f (Inv, Mat, Čl), is entitled as the:

i. technology function with parameters Inv (input demand), Mat (material) and Čl (man);
ii. economized function being enhanced with parameter Pe (finance);
iii. administration function being upgraded by parameter Adm (administrative); and
iv. informatized function being further upgraded with the additional parameter Inf (informatics);

finally the degree of the informatized production function is obtained:

$$E```= f````(Inv, Mat, Čl, Pe, Adm, Inf). \qquad (2.1.1.)$$

For these four degrees of the production function there are five verbally expressed resulting frames for axiomatic prediction of their effects in (Vlček, 1996; Vlček, 1999). While the effect of the 1st degree is based on a mutual connection of two function participants, the effect of the 2nd degree includes a relationship between connections of the 1st degree (so the sequence of unique relation pairs is generated), the effect of the 3rd degree is generated by the connection of relations among participants at the "plane" of the lower degree production function, etc. The effect of the 5th degree implements therefore "space", and the fourth imaginary dimension – time. This degree of the production function can be used only in very complicated tasks, for example in strategies and alliances of economic and political supersystems.

In further text we will utilize the way of reasoning and the formulation of the production function from (Vlček, 1996; Vlček, 1999), accepting the validity of the hypothesis that "enhancement of an effect is possible by extending the dimensionality of space, where the production function of the previous degree is valid".

Then it is advisable within this context to bring in the formula of an even higher degree:

$$E```` = f````(Inv, Mat, Čl, Pe, Adm, Inf, D), \qquad (2.1.2.)$$

reflecting the effect of sustainable development D, as well.

2.2. The Systems approaches - synergy

The foundations for a Systems approach (Vlček, 1984; Vlček, 1999; Vlček & Petr, 1983) are based on a respect for a reciprocity of parts, on an interface - on a structure and behavior of systems, on the emergence of synergy (Veselý, 2005) in Complex Hybrid Systems or Alliances. Defined Systems tools, as well as systems management, are based at first on Systems analysis, and second on Systems synthesis (Vlček, 1984; Vlček, 1999; Vlček & Petr, 1983). Both branches are simultaneously objects of interest, as well as tools and instruments for studying target tasks of Synergy, i.e., the multiplicative result of cooperation and collaboration of Systems parts. The very beginning of this study is (Veselý, 2005) the recognition, then definition of Systems alliance, which shows the creation of a system alliance via interactions, both internal and external (vide system analysis tasks on an interface in (Vlček, 1984; Vlček, 1999; Vlček & Petr, 1983)). The features of it are defined by synergy effects as a high-level internal quality emerging from the attributes of communicating parts. This synergy effect can be reflected - in the sense of production functions referred in (Vlček, 1996; Vlček, 1999) - as a specific form of an added value, as an origin of new value, what could be called an added output, generated from the efficiency of a function relationship of interacting parts of the System as a whole.

The branch of transportation (Vlček, 1996; Vlček, 1999) in concepts of the effects of the 4th and 5th grades is, (in the sense of thesis (Veselý, 2005)), a sufficiently complicated Hybrid System, or an Alliance of Systems, in which the synergy could emerge.

Nevertheless, the synergy is also a key factor if the concept of sustainable development is taken into account, as the study of the correspondence of parts of the system, as well as its external relations, is based on the research of synergy effects. This is why this research is carried out on the utilization of functions which implement in their arguments parameters of nature and living environment (or - in other words - all three linchpins of sustainable development). Therefore, synergy seems to be a proper tool for the further study and creation of the basic concepts of transportation as well.

2.3. Sustainable development

Three basic linchpins of the concept of sustainable development - economy, ecology and social responsibility – create, without doubt, a complex environment of human civilization (Míchal, 1976; Míchal, 1994; ÚÚR, 2000; WCED, 1987; ČR, 2004; ČR, 2006); within this framework input parameters are created and output values of production functions have an impact on them; this is why they have to be reflected in production functions.

A short summary of the content of the term sustainable development (Míchal, 1976; Míchal, 1994; ÚÚR, 2000; WCED, 1987; ČR, 2004; ČR, 2006) is feasible with references to the apparatus of informatics, or knowledge engineering (Vlček, 1999), i.e., simple data, items about nature and living environment. It could result in environmentally characterized information, or possibly implied (transitive) information up to knowledge, not only on a state of (eco)systems, but above all on the reasons and consequences of these states. Subsequently their qualified predictions lead to their systemization and arrangement into a System of principles and institutes of community's behavior, as well. Not only environmentally oriented, but also technocratic, branches of human activities study the specifications and limits of a balance between development and the further progress of (eco)systems (Míchal, 1976; Míchal, 1994; ÚÚR, 2000; WCED, 1987; ČR, 2004; ČR, 2006). This is the sense of declarations of the sustainability of the conceivable evolution of a civilized human society (Míchal, 1976; Míchal, 1994; ÚÚR, 2000; WCED, 1987; ČR, 2004; ČR, 2006). In the most frequent definition of the concept of sustainable development (EC, 2003; Mezřický et al., 2005; Říha, 2001; UN, 1992; UN-ECE, 2002, ÚÚR, 2000), it is stated, that sustainable development meets the needs of the contemporary generation, without threatening the living conditions for future generations. In other words it is a balanced relationship of:

- conditions for an acceptable natural environment,
- for economic development, and
- for the social cohesion of inhabitants.

The three linchpins of sustainable development, resulting from this definition (EC, 2003; Mezřický et al., 2005; Říha, 2001; UN, 1992; UN-ECE, 2002, ÚÚR, 2000), should be in mutual balance. By now (vide in (ČR, 2004)) social and economic views are applied rather intuitively, "practice" predominates more often, which results in short-term views, corresponding with political priorities, relating to periods of an electoral term and to criteria of a free market economy, and regulated by the minimization of economic investment return time.

The ecological linchpin implements the thesis that for continuing the physical sustainability of the evolution of the physical living environment the material and energy stream must fulfill three conditions (EC, 2003; Mezřický et al., 2005; Říha, 2001; UN, 1992; UN-ECE, 2002, ÚÚR, 2000):

a) the intensity of renewable resources usage is lower than the rate of their regeneration;
b) the intensity of nonrenewable resources usage is lower than the rate of the introduction of their sustainably renewable substitutes;
c) the intensity of pollution is lower than the assimilation capacity of the living environment.

However, up until now the economic increase, and the social enrichment enabled by this increase, has been consuming non-renewables, especially energetic resources. The same is valid for land usage for building and production activities (WCED, 1987; ČR, 2006; ČR, 2006).

The social linchpin postulates that in order to attain social sustainability a combination of population, funds and technologies has to be composed in such a way that the living standard has to be sufficient and consensual for every individual. The so-called Index of Human Development (United Nations Development Program, UNDP) is defined as a multiple index (EC, 2003; Mezřický et al., 2005; Říha, 2001; UN, 1992; UN-ECE, 2002, ÚÚR, 2000), compounded of three particular indicators with the same weight:

a) life expectancy at birth;
b) an access to education (a proportion of the number of literate adults to an average length of school education);
c) GDP per capita.

The economic linchpin reflects an economic increase. From the point of view of sustainability it is possible to consider the trend, in which an economic increase is reached by:

a) intensification,
b) technological or organizational innovation,
c) higher quality and human work efficiency (not by the further exploitation of natural resources).

It concerns the development and use of technologies which are environmentally friendly, as well as less energy usage and lower consumption of raw materials and removing environmental pollution from the past.

More generally:

- The law of conservation of energy / matter / information correlates with an ecology linchpin.
- The principle of entropy increase could be related to an economy linchpin.

3 THE FORMULATION OF THE RELATION: TRANSPORTATION - SYNERGY - SUSTAINABLE DEVELOPMENT

3.1. The fifth degree of production functions

An implementation of the sustainable development problems is, in fact, possible in two virtual dimensions:

I. "horizontally" as a completion of a further argument into the formula of a production function;
II. "vertically" as a certain specification of the argument D itself in the basic formula of production function. Consequently, we can study sustainable development as a specific feature of argument D, therefore we can speak about sustainable transportation.

In the first case we come to the discussion of a question of transportation as a science, particularly whether it is possible to understand sustainable development itself as a science, then - in analogy with formal notation in (Vlček, 1996) - to introduce (if we detach an orientation towards transportation):

A sustainable production function, leading to full-bodied reflection of sustainable development conditions in the form:

$$E````` = f`````(Inv, Mat, Čl, Pe, Adm, Inf, D, Udr) \quad (3.1.1.)$$

This variant is not analyzed in this article, because it is a significantly wider and more general one. It is de facto the primary task of transportation as a science.

If sustainable development is perceived as a determinate – but, regarding other matters, indispensable - specification of argument D, we can reformulate the relevant degree of the production function:

$$E```` = f````(Inv, Mat, Čl, Pe, Adm, Inf, D^{Udr}) \quad (3.1.2.)$$

extending the argument D^{Udr} into the form:

$$D^{Udr} = f^{Udr}(MetD, UloD, ParD) \quad (3.1.3.)$$

where:

MetD is to be understood as a complex of methods especially for the branch of transportation as a complex of scientific tasks of transportation (vide (Vlček, 1996)), dealing with applications of the principles of sustainable development.

ParD is to be taken as a complex of external parameters, enclosing a summary and space-time of UloD, of course constrained by the limits of the survival of the Systems (Alliance) as a whole, which are represented just by parameters, by characteristics, by criteria or limits of the sustainable development (that means by the parameters of a quality of the living environment, of a balance of the ecosystem with a coincidental global economy increase - in other words by the conformity of all three linchpins of sustainable development (vide WCED, 1987; ČR, 2006; ČR, 2006).

The goal of the study of synergy effects is "sustainable transportation": methods and processes of searching for optimal strategies of behavior and functions of transportation for both the preservation of development and life (Veselý, 2005). The increased qualitative effect on the System as a whole (Vlček, 1996) can be expected.

3.2. Reflections of demands on sustainable transportation in actual practices

The major cross-sectional and multidisciplinary area where the idea of sustainability is reflected is territorial planning. This area of human activity implements, in a summary of its methods, the very substance of a Systems approach to environmental changes - as well as logical and conceptual support for sustainability, not only of its own Systems Identity, but also of a Strategic Identity (Veselý, 2005; Vlček, 1984; Vlček, 1996; Vlček & Petr, 1983). Territorial planning (WCED, 1987; ČR, 2006; ČR, 2006) is (from the point of view of synergy) simply the area, dealing with Multi –Systems, Hybrid Systems or even with Alliances. Some of the typical tasks are:

- the relation among particular components of territorial planning activities,
- the tackling of complexity, heterogeneity and uncertainty,
- dealing with global, social, human, territorial and artificial components, taking into account human community behavior,
- the optimization of nature resources utilization,
- the solution of technology impacts on the environment,
- linking with modern technologies, economy, environmental activities and social problems.

From this point of view we can envisage territorial planning (WCED, 1987; ČR, 2006; ČR, 2006) (till now understood just as a one-track discipline) as a logical framework, including transportation in a wider sense (Vlček, 1996) as a transfer of material, energy and information / knowledge entities (Vlček, 1999) (e.g., the transfer of life styles, types of residential infrastructures, ideas of environment protection). In such a generalization of territorial planning, it is consequently possible to apply the principles of sustainable development together with technology and civilization progression, as well. Within this context the criteria and limits, resulting from processes such as EIA, SEA etc., are determined (WCED, 1987; ČR, 2006; ČR, 2006). The Systems Identity and conditions for its sustainability are formulated, as well as specific arguments for the formulation of production functions f```. They should illustrate their inherent synergy effects for the solution of transportation tasks with respect to the principles of sustainable development. Within this framework geographical information system – GIS (Dale, 2005; El-Hamied Hasen, 2000; Haines-Young, 1993; Vlčková, 2009; Vlčková, 2010; Vlčková - elaborated text), is characteristic as the sophisticated tool. GIS enables operations with spatial alias geographical data, with spatial - geographical information and consequently it also enables the generation and usage of spatial - geographical knowledge and experience (in the information sense of the word).

GIS can be implemented (Vlčková, 2009; Vlčková, 2010; Vlčková - elaborated text) at four basic application levels:

1. at the first level of a simple display of territory features,
2. at the next level of the modeling of territory features; the fundaments of it lie in generation of derived, transitive spatial information and its projection,
3. at the third level we can speak of the prediction of spatial features,
4. at the last level we have the supreme use of this tool - working within the GIS environment - which means that all solutions of problems, all processes are thoroughly outlined in GIS and they are based on computing, modeling and prediction methods and GIS-tools for the spatial analysis of all data and information.

In this sense it concerns not only the simple processing of "geographical" data, information and knowledge, but more extensive knowledge systems, as well as resulting in complex geographical information and geographical knowledge of environmental characteristics.

4 THE VISIONS

To summarize the basic content of the presented considerations the concept of "Synergy Transportation" could be introduced. Transportation, in such a meaning, embodies the attributes of synergy resulting from the basic features of the ternary relation Transportation / Human society / Sustainable Development.
To proceed further on the background of (Veselý, 2005; Vlček, 1996; Vlček, 1999), it is possible to utilize the ideas of theories of catastrophes and chaos and their complements, theories of ordering and self-organization to the analyzing, explaining and predictions of the behavior and emergences in Complex Hybrid Systems and Systems Alliances. The originals to these Systems entities are the wholes of Transportation and Communication, nested within the Human Society and placed on the Earth.

REFERENCES

Dale, Peter. 2005. *Introduction to mathematical techniques used in GIS.* CRC Press. Boca Raton . 0-415-33414-4.

El-Hamied Hassen, Tarek Abd. 2000. *Implementation of Geographic Information System (GIS) to support urban development analysis for decision making process.* Ph. D. thesis. CTU, FCE. Prague.

EUROPEAN COMMISSION (EC). 2003. *European Common Indicators (ECI).* Česká verze Společné evropské indikátory udržitelného rozvoje na místní úrovni. AmbienteItalia. http://www. reccr. cz/projektys/indikator/indikator. html, http://www. sustainable-cities. org/expert. html

Haines-Young, R. H. 1993. *Landscape ecology and geographic information systems.* CRC Press. London. 0-7484-0002-8.

Mezřický, Václav a kol. 2005. *Environmentální politika a udržitelný rozvoj.* Portál. Praha. 80-7367-003-8.

Míchal, Igor. 1976. *O odpovědném vztahu k přírodě - předpoklady ekologické etiky.* Pražské středisko státní památkové péče a ochrany přírody. Praha. 80-85368-22-6.

Míchal, Igor. 1994. *Ekologická stabilita.* Veronica. Brno.

Říha, Josef. 2001. *Nový fenomén - posuzování udržitelnosti.* Ochrana přírody 56/2, pp. 41-44.

UNITED NATIONS. 1992. *The Rio Declaration on Environment and Development.* UNO. New York.

UNITED NATIONS - ECONOMIC COUNCIL FOR EUROPE (UN-ECE). 2002. *Report from 9th Conference on Urban and Regional Research.* HBP/SEM 53/2.

UNITED NATIONS - ECONOMIC COUNCIL FOR EUROPE (UN-ECE). 2002. *Sharing.*

ÚSTAV ÚZEMNÍHO ROZVOJE. 2000. *Principy udržitelného územního rozvoje.* ÚÚR. Brno.

Veselý, Jaroslav. 2005. *Úvod do systémové strategie dopravy.* ČVUT. Praha. 80-01-03184-5.

Vlček, Jaroslav. 1984. *Metody systémového inženýrství.* SNTL. Praha.

Vlček, Jaroslav. 1996. *Doprava jako věda.* Doprava předmět vědeckého zkoumání - sborník příspěvků, kolokvium. Praha.

Vlček, Jaroslav. 1999. *Systémové inženýrství.* ČVUT. Praha. 80-01-01905-5.

Vlček, Jaroslav, Petr, Jan. 1983. *Analýza a projektování systémů.* ČVUT. Praha. skripta.

Vlčková, Veronika. 2010. *Geoznalost a geoinformační inženýrství.* GIS na ČVUT (sborník příspěvků). ČVUT, ARCDATA. Praha. 978-80-904450-2-4.

Vlčková, Veronika. 2009. *Co je GIS (nepublikovaná přednáška).*

Vlčková, Veronika. *Geoinformační inženýrství (dosud nepublikováno - rozpracovaný text).*

Wolf, Paul R. 1997. *Adjustment computations: statistics and least squares in surveying and GIS.* John Wiley & Sons. New York, Wiley. 0-471-16833-5.

WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT (WCED). 1987. *Our Common Future.* Oxford University Press. Oxford.

2004. *Strategie udržitelného rozvoje České republiky.* národní dokumenty ČR. Praha.

2006. *Responsibility: Redefining the public interest for territorial development.* Draft Report for the Conference on Urban and Regional Research.

2006. *Vyhláška MMR č, 500/2006 Sb. , o územně analytických podkladech, územně plánovací dokumentaci a způsobu evidence územně plánovací činnosti.* národní dokumenty ČR. Praha.

2006. *Zákon č. 183/2006 Sb. , o územním plánování a stavebním řádu (stavební zákon).* národní dokumenty ČR. Praha.

Dynamic Tests: Passenger Car vs. Child Pedestrian

Z. Schejbalová* & A. Kvášová
Faculty of Transportation Sciences, Czech Technical University in Prague, Prague, Czech Republic
** Corresponding author: schejbalova@fd.cvut.cz*

Z. Marek
Police Academy of Czech Republic, Prague, Czech Republic

DOI: 10.2478/v10158-010-0025-x

ABSTRACT: The Department of Forensic Experts in Transportation at the Faculty of Transportation Sciences performed a second set of dynamic passive safety tests on a passenger car (M1 category - Škoda Octavia II) in a child pedestrian collision. Initial and test conditions were similar to those that were made in the first set of tests in September 2009 (Škoda Roomster). Deformations of contact zones on the frontal vehicle surface were analyzed by 3D scanning technology (3D handy scanner). Head, thorax and pelvic resultant acceleration, acceleration of knee joint in sagittal direction and the contact force on the femoral structure of the dummy (P6 dummy, 1.17m; 22kg) were measured. The aim of these tests is not only to provide a detailed description of pedestrian kinematics and a comparison of primary and secondary impact seriousness, but also to provide a data source for advanced mathematical modeling.

KEY WORDS: Primary and secondary impact, child pedestrian, instrumentation, injury criteria.

1 INTRODUCTION

Pedestrian safety is nowadays a very important criterion for vehicle safety evaluation. Vehicle certification standards are based on vehicle frontal part testing with impactors which represent the certain body parts of an adult pedestrian. The risk of impact consequences for children is only tested through a head impactor test.

The Faculty of Transportation Sciences performed a second set of three dynamic passive safety tests for a passenger car (category M1 – Škoda Octavia II) in a child pedestrian collision. The tests were executed at different impact speeds (10, 20, 30 kmph), analogous to the first set of tests carried out in September 2009 with a Škoda Roomster. It was clear from the first set of tests that several body parts are more threatened than the head during a primary impact with a vehicle. The resultant acceleration of the head, thorax and pelvis were measured using child dummy P6. The dummy was modified because of the demand for a higher number of measuring areas than in the case of the original P6 dummy, which is intended for child restraints testing. The left upper leg was equipped with two strain-gauge half bridges on the femoral skeleton for contact force measurement. One uniaxial accelerometer was installed in the knee area for the measurement of acceleration in the sagittal direction. Deformations of contact zones on the frontal vehicle surface were analyzed using 3D scanning technology.

Initial and test conditions were similar to those used for tests in 2009. Acceleration measurement was made using new equipment. The aim of this second set of tests was to identify and verify critical contact zones on the vehicle frontal part regarding the pelvic and femoral part of the dummy, and to compare the results with the previous set of tests carried out with the Škoda Roomster.

2 EXPERIMENT

2.1 Conditions

With respect to the technical specifications and the possibility of comparability with previous measurements, the following initial conditions were formulated:

a) collision of passenger car (M1 category),
b) P6 dummy, (6 years; 1.17m; 22kg) which was adapted for the test – mentioned above (Note: There is no child dummy which is specified for full-scale pedestrian – vehicle crash tests).
c) dummy position: the dummy was facing the approaching vehicle, heel standing in the longitudinal axis of the vehicle (see Figure 1),
d) proposed collision speeds: 10, 20, 30 kmph,
e) vehicle is starting to break at the moment of crash contact.

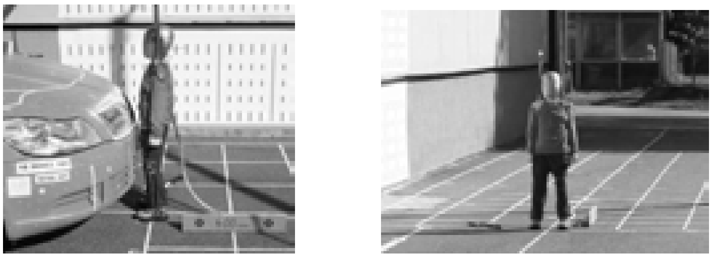

Figure 1: Initial dummy possition.

Measured quantities:
- a real vehicle speed, vehicle acceleration (3D),
- acceleration time flow of dummy (according to dummy instrumentation),
- contact force time flow in the femur,
- high speed video recording,
- dimensional characteristics of the process (initial and final location of colliding object),
- 3D scanning of contact zones after collision and car damage.

Dummy instrumentation (see Figure 2):
- head: 3-axis accelerometer, directions x,y,z, 1000 g range,
- thorax: 3-axis accelerometer, directions x,y,z, 1000 g range,
- pelvic region: 3-axis accelerometer, directions x,y,z, 500 g range,
- knee joint: 1-axis accelerometer, direction x, 500 g range,
- upper leg: femoral skeleton – two strain-gauge halfbridges, uniaxial state of stress.

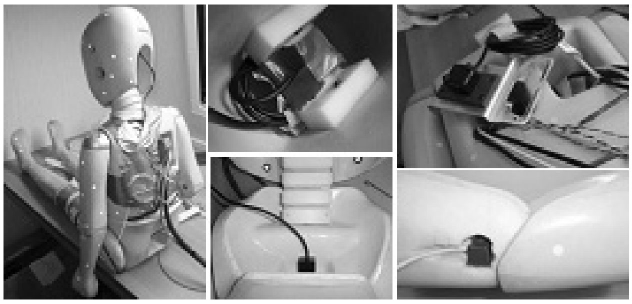

Figure 2: Dummy instrumentation.

Passenger car Škoda Octavia II, 1.4 MPI:

- maximum power: 59 kW
- total displacement: 1390 cm^3
- curb weight: 1255 kg
- the car was equipped with an antireflection coating and impact zones on the bonnet due to 2003/102/EC directive were marked.

3 TIME COURSE OF THE EXPERIMENT

Three tests were made at a real impact speed 12.2 kmph (test No. 101), 22.4 kmph (test No. 201) and 30.6 kmph (test No. 301).

The following sequence demonstrates the time course of the test No. 301, impact speed 30.6 kmph.

Time of the first contact of the dummy with the vehicle: t_{s301} = 3 ms.

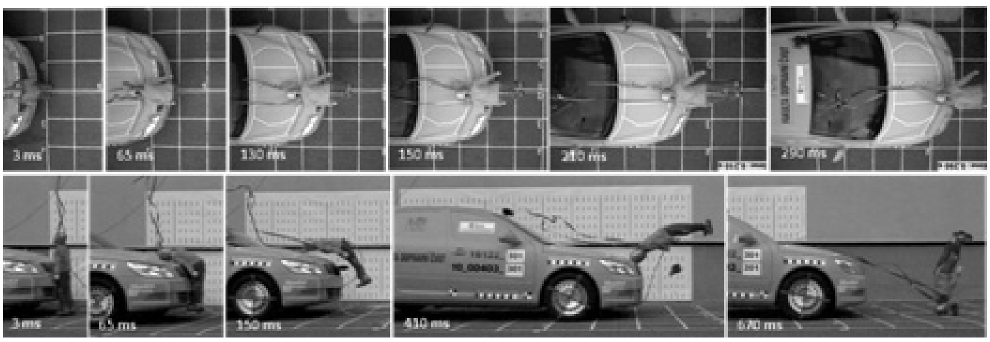

Figure 3a: Time course of the test No. 301.

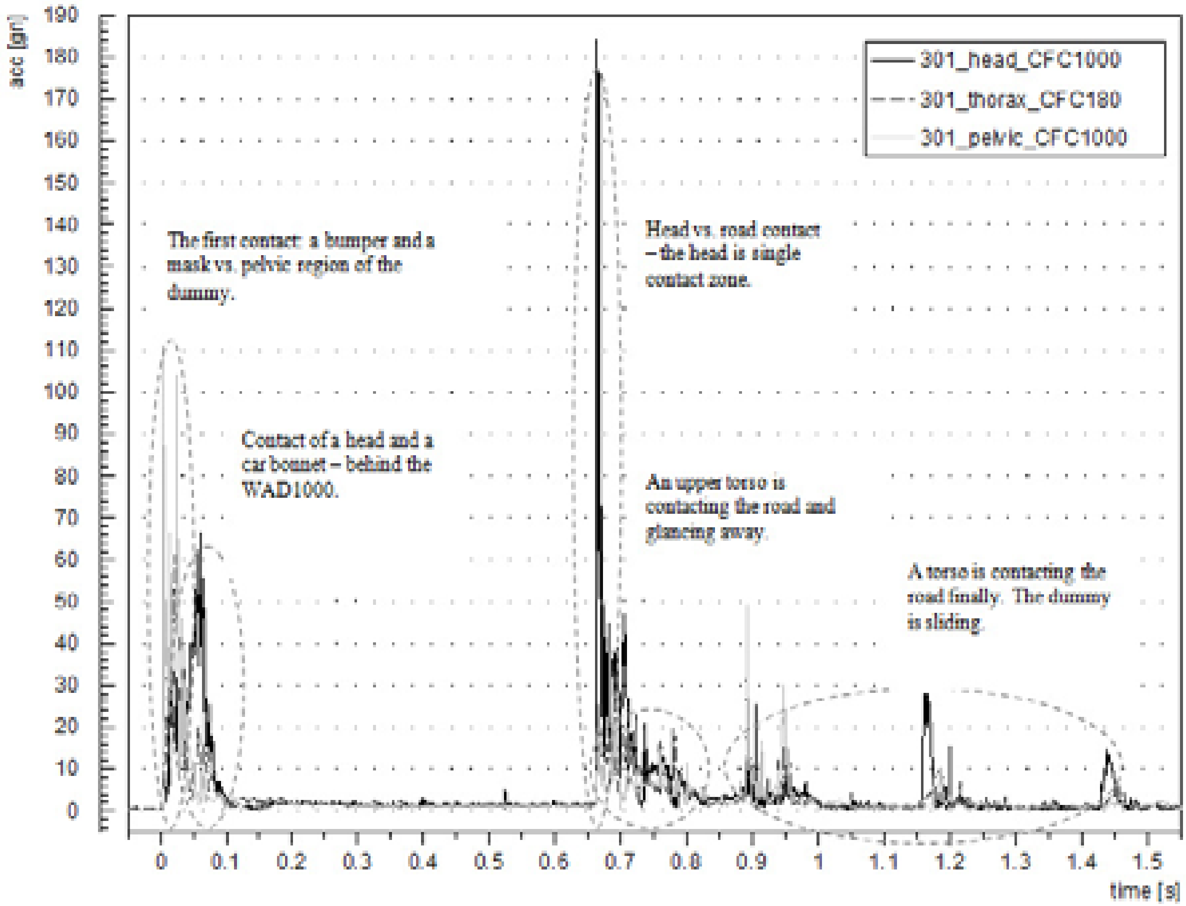

Figure 3b: Time course of the test No. 301.

4 RESULTS

4.1 Biomechanical criteria values

Injury criteria - head: HPC and 3ms

Head performance criterion is defined by the following formula:

$$HPC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a.dt \right]^{2,5} (t_2 - t_1), \text{ where}$$

a = resultant acceleration in g, t_1 a t_2 = time points, which determines the beginning and end of the time interval, where HPC value is maximum. HPC limit value is 1000. According to the US standard FMVSS 208 "Occupant crash protection" HPC_{15} limit value in the case of a 6-year-old child reaches 700.

HPC measured values 3ms criterion is applicable, not only to head performance, but also to other body segments. Limit value for head is 80 g. Criterion interpretation: Acceleration higher than 80g must not act longer than 3ms.

According to the US standard FMVSS 208 "Occupant crash protection" HPC15 limit value in the case of 6-year-old child reaches 60g. 3ms measured values (see Table 1).

Table 1: Head performance criterion (HPC) and 3ms criterion.

test no:	velocity	Primary impact HPC_{15}		Secondary impact HPC_{15}		Primary impact a3ms		Secondary impact a3ms	
	[kmph]	[-]	limit	[-]	limit	[g]	limit	[g]	limit
101	12.2	**58.2**	1000/700	**135.6**	1000/700	**33.7**	80/60	**52.8**	80/60
201	22.4	**58.3**	1000/700	**554.8**	1000/700	**26.1**	80/60	**49.7**	80/60
301	30.6	**251.3**	1000/700	**862.7**	1000/700	**46.6**	80/60	**88.7**	80/60

3ms injury criteria – thorax

Limit value of this criterion in the case of the thorax is 60 g. According to standard ECE 44 "Child restraints systems" the limit value in the case of a 6-year-old child reaches 55 g. Measured values (see Table. 2):

Table 2: 3ms criterion – thorax.

test no:	velocity	Primary impact a3ms		Secondary impact a3ms	
	[kmph]	[g]	limit	[g]	limit
101	12.2	**13.6**	60/55	**19.3**	60/55
201	22.4	**38.9**	60/55	**21.7**	60/55
301	30.6	**50.9**	60/55	**22.9**	60/55

a_{max} injury criteria – pelvic

Maximum acceleration value must not exceed 130 g (see Table 3).

Table 3: 3ms criterion – pelvic.

test no:	velocity	Primary impact a_{max}		Secondary impact a_{max}	
	[kmph]	[g]	limit	[g]	limit
101	12.2	**37.1**	130	**36.6**	130
201	22.4	**65.9**	130	**44.2**	130
301	30.6	**111.4**	130	**39.1**	130

Femur injury criteria – contact force

Bending femur tolerance is not strictly defined. In the case of an adult femur the following bending limits are frequently published: 1.5 kN to 4 kN. Levine (2002) published a bending limit value till rupture of 3.92 kN for men and 2.58 kN for women. Yamada (1970) published the maximum bending limit till specimen rupture in relation to donor's age. In the group from 20 to 39 years the limit is cca 2.8 kN in case of 260 mm^2 femur cortical bone cross-sectional area and bending strength 212 N/mm^2. In the children group of around 6 years Yamada published the same level of bending strength, the femur has a higher level of plasticity and is able to absorb more energy till rupture, the cross-sectional area of the cortical bone is smaller. For measured values see Figure 4 and Table 4.

Table 4: Maximum contact force – femur.

test no:	Primary impact F_{max}	
	[N]	t [ms]
101	**877**	55
201	**2497**	35.5
301	**3418**	26.2

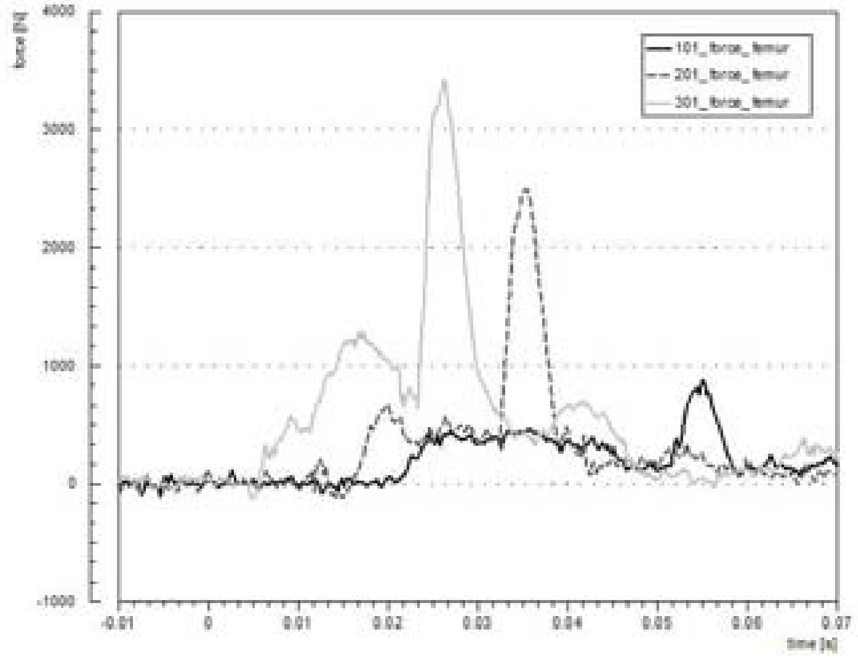

Figure 4: Femur contact force time course.

Knee acceleration

Maximum acceleration value must not exceed 170 g. Measured values are in Table 5.

Table 5: Maximum knee acceleration in x direction.

test no:	Primary impact		Secondary impact	
	a_{max}		a_{max}	
	[g]	limit	[g]	limit
101	**74.6**	170	**50.5**	170
201	**186.8**	170	**96**	170
301	**210.4**	170	**54.2**	170

4.2 3D scanning – 3D data digitalization

3D scanning is a process of data digitalization; the goal is to express the real object in a virtual (mathematical) way. This method of digitalization is able to record space or solids effectively.

The result of 3D digitalization is “a point cloud” where the position of every single point is detected by a 3D scanner. This type of application in connection with the formulated task allows the recording of damage to a car body after a crash test.

Method requirements: mobility of device, limited time for scanning (max. 15 minutes for one scanning series), scanning accuracy (in 0.01mm), reliability of the device, data quality, non-contact scanning, outdoor performance, variable lightning conditions, availability of scanned object position change, scanning interruption, “easy” data processing, real time result visualization (data verification).

With respect to the facts mentioned above, the Handyscan type MAXScan from CreaForm was chosen for this application. The advantage of this type of scanner is the possibility of a relative motion of the scanner and scanned object. The scanner identifies position markings on the scanned object and two cameras record the laser intersection, which is projected on the object.

For the car body deformation scanning, parts on the vehicle front (bumper, hood, fenders, front grill) were covered with reflex targets. The original vehicle frontal parts were fitted appropriately and scanned because of the following comparison with those that were damaged by the crash test. 3D analysis is based on 3D surfaces comparison.

The results from the test 101/201/301 (12.2 kmph/22.4 kmph/30.6 kmph) show that the dummy head impact caused plastic deformation of the hood of 13.2 mm/23.7mm/20mm (depth), the rear central part of the hood was deflected in test 101 on average by 1.5mm. The dummy head's contact point is revealed by the dark area on the deformation map, the lifted area of the hood in test 201/301 reached a maximum of 6.7 mm/8.8mm.

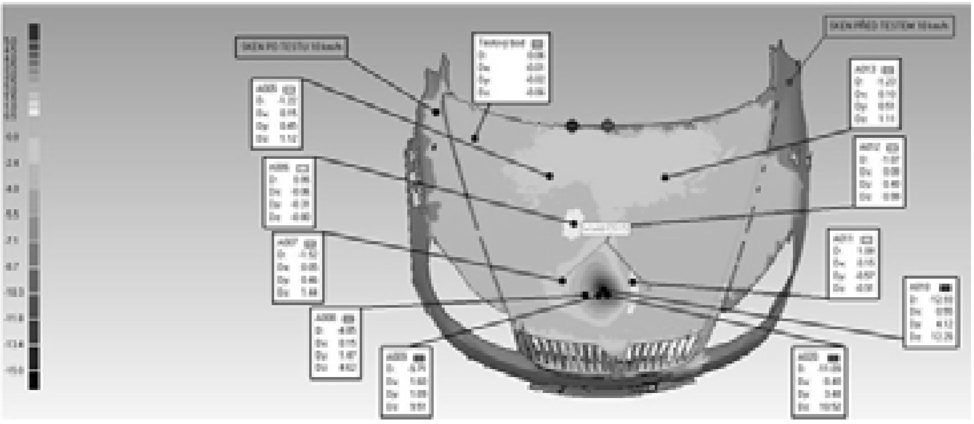

Figure 5: 3D analysis and deformation map for the test 101, 12.2 kmph.

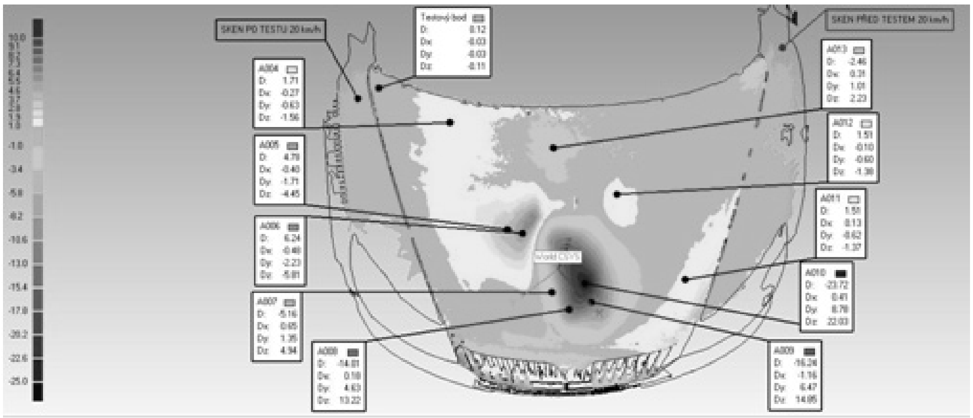

Figure 6: 3D analysis and deformation map for the test 201, 22.4 kmph.

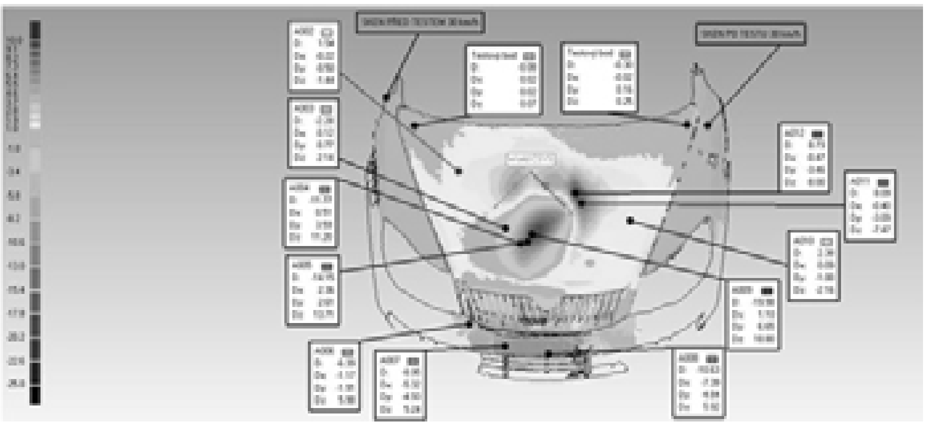

Figure 7: 3D analysis and deformation map for the test 301, 30.6 kmph.

5 DISCUSSION

5.1 Head injuries

Neither Head Performance Criteria (HPC), nor 3ms injury criteria limit value was exceeded in the primary head impact for all performed tests. The head contacted with the car bonnet behind the WAD1000 line.

The values of the biomechanical criteria are several times larger for the secondary impact than for the primary one. The limit value for the secondary impact was only exceeded in the case of test No. 301 (30.6 kmph), the 3ms criteria was in this case exceeded by over 10 %. According to the US standards (FMVSS 208 “Occupant crash protection”), the value of HPC15 also exceeded the defined limit (limit 700) for a 6-year-old child.

Based on the test and video analysis, the analysis of a secondary contact with the road surface, it is obvious that neither the HPC value nor the 3ms criteria objectively represent the seriousness of the secondary impact. The reason is probably a mechanism of dominating flexion and extension motion in neck spine and the head skidding on the road surface. This conclusion corresponds to previous experiments made in 2009.

5.2 Thorax injuries

The limit value of 3ms criteria for a 6-year-old child’s thorax (55 g according to the EHK 44) was not exceeded in any executed test. This value is close to the limit in test No. 301 for primary impact. For the secondary impact, there is no critical acceleration because of the kinematics of the pedestrian after the collision. The secondary contact was taken mostly via head and neck.

5.3 Pelvic area injuries

The maximum acceleration limit a_{max} 130g was not exceeded in any executed test for the primary or secondary impact. The pelvic area is a point of first contact with the car’s frontend, it is clearly seen from the graphic representation of acceleration and video records made by a high speed (HS) camera. The highest acceleration values for the pelvic area were measured at primary contact. There is a presumption of contusion of abdominal organs and the risk of pelvic fracture (symphysis pubic). The pelvic and knee areas were the most loaded parts of the body within the experimental series.

5.4 Knee injuries

The limit value of maximum acceleration for the knee (170 g) was exceeded in test No. 201 and 301 (primary impact). Injury of the knee joint or a fracture of a crus (on epiphysis or metaphysis) is highly probable.

5.5 Femur contact force

The limit value of maximum contact force on the femoral skeleton is not exactly defined. On the basis of research, we can say that the average biomechanical limit for contact force was exceeded at primary impact in test No. 301. In this case a femur fracture can be predicted. The impact force on the femoral skeleton was calculated from axial strain with a knowledge of material properties.

5.6 Secondary impact remarks

HPC seems to be an indicator of secondary impact seriousness regarding the fact that in all tests it reached higher values than in primary contact with the vehicle’s frontal part. An interesting observation is that in the case of other body parts the results were inverse – the primary impact was the one with more serious consequences regarding biomechanical criteria values calculated for dynamical impacts of certain body parts in direct interaction with a vehicle’s frontal part.

5.7 Comparison with previous set of test with Škoda Roomster

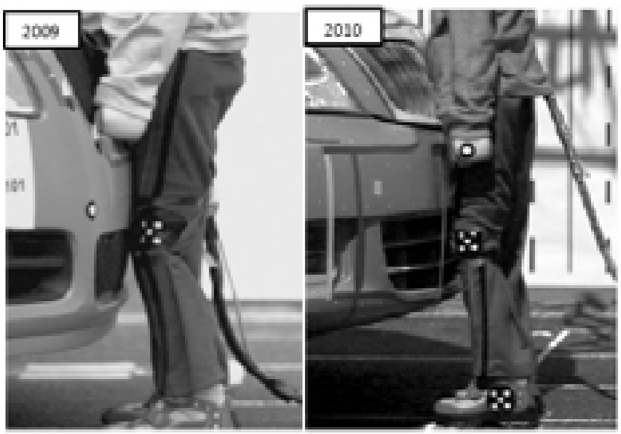

Figure 8: Primary contact with the vehicle’s frontal part (2009 – Škoda Roomster, 2010 – Škoda Octavia II.)

Head: smoother shape of the primary collision acceleration curve in the Škoda Roomster – mainly under lower speed of collision, lower HPC and 3ms values.

Thorax: smoother shape of the primary collision acceleration curve in the Škoda Roomster – under lower speed of collision, lower values of acceleration.

Pelvic: higher maximum acceleration value in the primary collision in the Škoda Octavia II – mainly under higher speed of collision (pelvis was the initial contact zone in the Škoda Octavia II test – see Figure 8).

Femoral skeleton: slightly higher maximum contact force value in the Škoda Roomster test (the femoral part with the knee joint was the initial contact zone in the Škoda Roomster test - see Figure 8).

6 CONCLUSION

The CTU in Prague, Faculty of Transportation Sciences, performed a second set of dynamic passive safety tests on a passenger car (Škoda Octavia II) collision with a P6 dummy. The specific conclusions and findings are in the discussion part of this paper.

The most significant finding is that in the primary collision the pelvic and femoral part are the most threatened parts of a child pedestrian’s body when in collision with a vehicle.

There are slight differences in acceleration or force loading regarding the vehicle's frontal shape. Nevertheless, from the results it is obvious that it is necessary to focus on the action of force to the upper and lower leg at primary contact and the necessity of force moment and acceleration measurement on the neck of the dummy – for the reasons of analysis of secondary impact seriousness. It is a very complex issue which requires further deep research; for example, to choose the factors that can significantly influence the post-crash kinematics and perform numerical analysis of a response to factors variation. According to the presented research it will be desirable to propose Regulation No 78/2009 amendment with respect to child impactor testing distribution (pelvic and legform test).

Although primary impact consequences can be positively affected by a vehicle's construction, the secondary ones can not be influenced significantly and still represent a critical danger for a pedestrian's head which can be eliminated only by prevention measures.

ACKNOWLEDGEMENT

This contribution is supported by MSM6840770043, Škoda Auto, a.s., TÜV SÜD Czech s.r.o., A.L.C.Z. a.s., Solid Vision s.r.o.

REFERENCES

Berg F. A., Egelhaaf M., Bakker J., Burkle H., Herrmann R., Scheerer J.: *Pedestrian Protection in Europe -The Potential of Car Design and Impact Testing*, DEKRA Automobil GmbH, Accident Research and DaimlerChrysler AG, Accident Research

http://www.unece.org/trans/doc/2002/wp29grsp/inf-gr-ps-13e.pdf

Nahum A. M., Melvin J.,W.: *Accidental Injury – Biomechanics and prevention*, ISBN 0-387-98820-3, Springer, 2002

DIRECTIVE 2003/102/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 November 2003 relating to the protection of pedestrians and other vulnerable road users before and in the event of a collision with a motor vehicle and amending Council Directive 70/156/EEC

IHRA INJURY BREAKDOWN

http://www.unece.org/trans/doc/2005/wp29grsp/ps-140e.pdf

IHRA/PS-WG PEDESTRIAN TRAFFIC ACCIDENT DATA

http://www.unece.org/trans/doc/2003/wp29grsp/ps-31.doc

Legislation EHK44 – Child restraints systems

Legislation FMVSS 208 – "Occupant crash protection"

REGULATION (EC) No 78/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 January 2009 on the type-approval of motor vehicles with regard to the protection of pedestrians and other vulnerable road users, amending Directive 2007/46/EC and repealing Directives 2003/102/EC and 2005/66/EC

Technical Note on Design of Suspension Parameters for FSAE Vehicle

O. Suchomel*
CULS Prague, Technical Faculty, Department of Vehicles and Ground Transport, Prague, Czech Republic

B. Ruzicka
University of Technology Brno, Faculty of Mechanical Engineering, Institute of Machine and Industrial Design, Brno, Czech Republic

** Corresponding author: suchomel@tf.czu.cz*

ABSTRACT: Correct suspension parameters determination is one of the most important design issues in the development of each type of car. The aim of the suspension design in the field of race cars is to provide ideal operating conditions for the tire and to allow it to generate the maximum amount of traction, braking and lateral forces which determine a vehicle’s acceleration capabilities. This article describes the determination of the Formula Student/SAE car suspension parameters related to the vertical dynamics of the car as a basic point in tuning up the suspension on the car itself in real operating conditions.

KEYWORDS: Suspension parameters, spring rate, damping rate, Formula Student/SAE.

1 INTRODUCTION

Suspension is one of the most important pieces of equipment on each car. It has different functions: it carries all the vehicle’s loads; maintains the correct wheel alignment to the ground; reduces the effect of shock forces when passing ground disturbances; controls the vehicle’s longitudinal and lateral speed, and maintains the tire contact patch in contact with the ground for the maximum time possible. The mentioned requirements are provided by different suspensions parts divided into the guiding elements and force generating elements. In the following articles, the procedure for the determination of the spring rate and damping rate is presented. The numerical values of the mentioned constants are computed for a Formula Student/SAE car and later used when building the real Formula Student/SAE car at CULS Prague.

2 DETERMINATION OF SPRING RATES

The described approach for the determination of all the necessary suspension parameters related to the vertical dynamics is based on a quarter-sized car model. The basic points for the suspension design parameters are the mass properties of the vehicle (see tab.1).

Table 1: Vehicle mass properties.

Constant	**Value**	**Unit**	**Signification**
m	300	[kg]	overall vehicle mass
w_F / w_R	45 / 55	[% / %]	mass distribution related to front / rear axis
$m_F = w_F m$	135	[kg]	overall mass on front axis
$m_R = w_R m$	165	[kg]	overall mass on rear axis
m_{uF}	27.78	[kg]	overall unsprung mass on front axis
m_{uR}	29.11	[kg]	overall unsprung mass on rear axis
$m_{sF} = m_F - m_{UF}$	107.22	[kg]	overall sprung mass on front axis
$m_{sR} = m_R - m_{UR}$	135.89	[kg]	overall sprung mass on rear

According the suggestions from literature (Milliken & Milliken 1995) for low-downforced racing cars, the initial choice of ride frequencies is as follow: front ride frequency f_{nF} = 2.1 Hz, rear ride frequency, f_{nR} = 1.9 Hz Then ride rates for front K_{rF} and rear K_{rF} end of the vehicle, with respect to corner (either left or right which equals).

$$f_{nF,R} = \frac{1}{2\pi}\sqrt{\frac{K_{rF,R}}{\frac{m_{sF,R}}{2}}}, \qquad K_{rF,R} = (2\pi f_{nF,R})^2 \frac{m_{sF,R}}{2}$$

$$K_{rF} = (2\pi.2,1)^2 \frac{107,22}{2} = 9333,67 Nm^{-1} \qquad K_{rR} = (2\pi.1,9)^2 \frac{135,89}{2} = 9683,61 Nm^{-1}$$

With spring rate $K_t = 125000 Nm^{-1}$ of chosen tire Hoosier 20x7.5x13 - pressure 14 PSI (Honzík , 2008)

$$K_{wF,R} = \frac{K_{rF,R} K_t}{K_t - K_{rF,R}}$$

$$K_{wF} = \frac{9333,67.125000}{125000 - 9333,67} = 10086,84 Nm^{-1} \qquad K_{wR} = \frac{9683,61.125000}{125000 - 9683,61} = 10496,78 Nm^{-1}$$

Final real spring rates $K_{sF,R}$ must be recalculated using the so-called "installation ratio" IR (Milliken & Milliken, 1995) defined as rate of change of spring compression with wheel movement. To slightly simplify the non-linear function for pull-rod type suspension, installation ratios have to be dealt with as a constant $IR_F = IR_F(0) = 1{,}5$ and $IR_R = IR_R(0) = 1{,}4$. Then

$$K_{sF} = \frac{K_{wF}}{IR_F^2} = \frac{10086{,}84}{1{,}5^2} = 4483{,}04 Nm^{-1} \qquad K_{sR} = \frac{K_{wR}}{IR_R^2} = \frac{10496{,}78}{1{,}4^2} = 5355{,}5 Nm^{-1}$$

3 CALCULATION OF ANTI-ROLL BAR PARAMETERS FOR DESIRED ROLL GRADIENTS

Roll gradient $RG[deg/g]$ gives information on how much the body rolls due to the lateral acceleration of the whole car. The desired set up is up to 1.5° / 1g, referred to by suggestions given in (Milliken & Milliken, 1995) as the Formula Student/SAE car achieved a max. lateral acceleration of about 1.5g. At first, roll stiffness is computed using front and rear track ($t_F = 1{,}230m$, $t_R = 1{,}205m$), spring rates $K_{wF,R}$.

$$K_{\varphi F} = \frac{1}{2} K_{wF} t_F^{\,2} = 0{,}5.10086{,}84.1{,}230^2 = 7630{,}19 \frac{Nm}{rad} = 133{,}17 \frac{Nm}{deg}$$

$$K_{\varphi R} = \frac{1}{2} K_{wR} t_R^{\,2} = 0{,}5.10496{,}78.1{,}205^2 = 7620{,}8 \frac{Nm}{rad} = 133{,}01 \frac{Nm}{deg}$$

The next step in the determination of anti-roll bars is the computation (Milliken & Milliken, 1995) of the height of the center of gravity of the sprung mass h_S , sprung mass distribution a_S and rolling moment lever arm h_{RM} (with the help of used variables: height of the center of gravity of the whole car $h = 0{,}38m$, wheel radius $r_F = 0{,}26m$, $r_R = 0{,}26m$, and front / rear roll center heights $z_F = 0{,}04m$, $z_R = 0{,}06m$).

$$h_s = \frac{mh - m_{uF} r_F - m_{uR} r_R}{(m_{sF} + m_{sR})} = \frac{300.0{,}38 - 27{,}78.0{,}26 - 29{,}11.0{,}26}{107{,}22 + 135{,}89} = 0{,}371m$$

$$a_S = \frac{m_{sF}}{m_{sF} + m_{sR}} = \frac{107{,}22}{107{,}22 + 135{,}89} = 0{,}44$$

$$h_{RM} = h_S - [z_F - (z_R - z_F)(1 - a_S)] = 0{,}347 - [0{,}04 - (0{,}06 - 0{,}04) * (1 - 0{,}44)] = 0{,}319m$$

For anti-roll bars stiffness $K_{\varphi B}$, the calculation of the rolling moment per 1g of lateral acceleration, M_{φ} / A_{y} and the computation of the overall desired roll stiffness K_{φ} is required.

$$\frac{M_{\varphi}}{A_{y}} = h_{RM}\left(m_{sF} + msR\right)g = 0{,}319.\left(107{,}22 + 135{,}89\right).9{,}81 = 762{,}9Nm$$

$$K_{\varphi} = \frac{M_{\varphi} / A_{y}}{RG} = \frac{762{,}9}{1.5} = 508{,}6N.m / deg$$

$$K_{\varphi B} = K_{\varphi} - K_{\varphi F} - K_{\varphi R} = 508{,}6 - 133{,}17 - 133{,}01 = 242{,}42Nm / deg$$

The recommendation (Milliken & Milliken, 1995) is to start with a total lateral load distribution to be 5% more than the weight distribution wF at the front axle. Based on this fact, the required anti-roll bar stiffness for the front and rear axle $K_{\varphi B\,F,R}$ is determined from the overall desired roll stiffness K_{φ} as follows

$$K_{\varphi B\,F} = K_{\varphi}\ .\ (\frac{w_{F} + 5}{100})\ -\ K_{\varphi F} = 508.6\ .\ (\frac{45 + 5}{100}) - 133.17 = 121.13\ \ Nm / deg$$

$$K_{\varphi B\,R} = K_{\varphi B}\ -\ K_{\varphi B\,F} = 242.42 - 121.13 = 121.29\ \ Nm / deg$$

Because the anti-roll bar installation ratio $IR_{AB\,F,R}$ (the rate of anti-roll bar displacement / roll with body roll) is expected to be the same as the ratio for the springs $IR_{AB\,F} = IR_{AB\,F}\left(0\right) = 1{,}5$ and $IR_{AB\,R} = IR_{AB\,R}\left(0\right) = 1{,}4$, then the final front and rear anti-roll bar stiffness $K_{\varphi AB\,F,R}$ is :

$$K_{\varphi AB\,F} = \frac{K_{\varphi B\,F}}{IR_{AB\,F}^{2}} = \frac{121{,}13}{1{,}5^{2}} = 53{,}83\ \ Nm / deg$$

$$K_{\varphi AB\,F} = \frac{K_{\varphi B\,R}}{IR_{AB\,R}^{2}} = \frac{121{,}29}{1{,}4^{2}} = 61{,}88\ \ Nm / deg$$

4 DETERMINATION OF DAMPING COEFFICIENTS

The baseline mean ride damping coefficients for each wheel of the front C_{brF} and rear axle C_{brR} result from the critical damping values $C_{brFcrit}$, $C_{brRcrit}$ (the critical damping coefficients of the sprung mass) multiplied by the recommended (Milliken & Milliken, 1995) damping ratios for the front and rear axle $\zeta_F = 0,4$, resp. $\zeta_R = 0,45$.

$$C_{brFcrit} = 2\sqrt{\frac{m_{sF}}{2} K_{wF}} = 2\sqrt{\left(\frac{107,22}{2} 10008,84\right)} = 1470,73 \frac{Ns}{m}$$

$$C_{brRcrit} = 2\sqrt{\frac{m_{sR}}{2} K_{wR}} = 2\sqrt{\left(\frac{135,89}{2} 10496,78\right)} = 1689,05 \frac{Ns}{m}$$

$$C_{brF} = \zeta_F C_{brFcrit} = 0,4.1470,73 = 588,29 \frac{Ns}{m}$$

$$C_{brR} = \zeta_R C_{brRcrit} = 0,45.1689,05 = 760,07 \frac{Ns}{m}$$

To obtain the final values of the mean damping coefficients set-up on the dampers, $C_{F,R}$, these must be corrected by the corresponding installation ratio again

$$C_F = \frac{C_{brF}}{IR^2} = \frac{588,29}{1,5^2} = 261,46 \frac{Ns}{m} , \qquad C_R = \frac{C_{brR}}{IR^2} = \frac{760,07}{1,4^2} = 387,79 \frac{Ns}{m}$$

For better control of resonance and the energy released by the spring, more damping force is required by the damper during the rebound (bilinear model). This asymmetry for compression C_C and extension C_E damping is expressed by the compression/extension ratio $R_{CE} = \frac{C_C}{C_E}$ with a typically value 0.4 as recommended from (Dixon, 1999).

Then, the modified damping coefficients, as a starting point for the next suspension tuning for the linear progressivity of compression and extension, are calculated for both axles as follows

$$C_{EF} = \frac{2\,C_F}{1+R_{CE}} = \frac{2\,.261{,}46}{1+0{,}4} = 373.51\ \frac{Ns}{m}\,, \quad C_{CF} = R_{CE}\,C_{EF} = 149.41\ \frac{Ns}{m}$$

$$C_{ER} = \frac{2\,C_R}{1+R_{CE}} = \frac{2\,.387{,}79}{1+0{,}4} = 553.99\ \frac{Ns}{m}\,, \quad C_{CR} = R_{CE}\,C_{ER} = 221.59\ \frac{Ns}{m}$$

5 CONCLUSIONS

This paper presents an approach for the determination of basic suspension parameters - spring stiffness, anti-roll bar stiffness and damping coefficients. The approach is based on linear vibrations dynamics and semi-experimental recommendations for the choice of basic constants. The presented approach can be applied for any road racing vehicle.

ACKNOWLEDGEMENTS

This paper was supported by the Internal Grant Agency of the Technical Faculty at the Czech University of Life Sciences. The paper was created in the Formula Student/SAE project at TF CULS.

REFERENCES

Milliken, W., Milliken D. , 1995. *Race Car Vehicle Dynamics.* SAE, 1995.

Honzík T., 2008. *Front Axle Design for Formula SAE*. VUT Brno

Rill, G. : *Vehicle dynamics. Lecture notes, October 2007*. Fachhochshule Regensburg.

Available on http://homepages.fhregensburg.de/~rig39165/skripte/Vehicle_Dynamics.pdf

Dixon, J. : 1999 , *The Shock Absorbers Handbook* , SAE 1999

Index of Titles

Volume 3/ 2010

Index of Authors

Volume 3/ 2010

Instructions to the autors

1 GENERAL GUIDELINES

Papers based on accepted abstracts and prepared in accordance to these guidelines are to be submitted through the journal's web site www.transportsciences.org. All papers, using Microsoft Word2000 (or newer) are limited to a size of at least 4 and no more than 8 single-spaced pages on A4 paper size (297 mm X 210 mm), including figures, tables, and references and should have an even number of pages. The paper's top, bottom, right and left margins must be 2.5 cm. No headers, footers and page numbers should be inserted.

2 TITLE, AUTHORS, AFFILIATIONS

The title of the paper must be in title letters, Times New Roman, font size 16, and aligned left. Use more than one line if necessary, but always use single-line spacing (without blank lines). Then, after one blank line, aligned left, type the First Author's name (first the initial of the first name, then the last name). If any of the co-authors have the same affiliation as the first author, add his/her name after an & (or a comma if more names follow). In the following line type the institution details (Name of the institution, City, State/Province, Country and e-mail address of a corresponding author). If there are authors linked to other institutions, after a blank line, repeat this procedure. The authors name must be in Times New Roman, regular, and font size 12. The institution details
must be in Times New Roman, italic, and font size 10.

3 ABSTRACT

The abstract should start after leaving eight blank lines. Type the text of the abstract in one paragraph, after a space behind the word abstract and colon, with a maximum of 250 words in Times New Roman, regular, font size 12, single-spaced, and justified. After leaving one blank line, type KEY WORDS: (capital letters, Times New Roman, font size 12), followed by a maximum of five (5) key words separated by commas. Only the first letter of the first key word should be capitalized.

4 THE TEXT

The main body of the paper follows the key words, after two blank lines (i.e., two blank lines between the first heading and the key words). The body text should be typed in Times New Roman, font size 12 and justified. The first line of the paragraphs should be indented 5 mm except the paragraphs that follow heading or subheading (i.e., the first line of the paragraphs that follow heading or subheading should not be indented). Never use bold and never underline any body text.

4.1 HEADINGS AND SUBHEADINGS

The headings are in capital letters, Times New Roman, font size 12. Subheadings are in title letters Times New Roman, font size 12. The headings and subheadings must be aligned left and should not be indented. Leave two blank lines before and one after the heading. There should be one (1) blank line before and after the subheadings. All headings and subheadings must be numbered. If a heading or subheading falls at the bottom of a page it should be transferred to the top of the next page.

4.2 FIGURES AND TABLES

Figures, line drawings, photographs, tables should be placed in the appropriate location, aligned centre, and positioned close to the citation in the document. They should have a caption, Times New Roman font size 12, with a colon dividing the figure number and the title (Figure 1: Material properties) and should be numbered consecutively, e.g. Figure 1, Figure 2, Table 1, and Table 2.

4.3 REFERENCES

At the end of the paper, list all references with the last name of the first author in alphabetical order, underneath the heading REFERENCES, as in the example. The title of the referred publication should be in italic while the rest of the reference description should be in regular letters. References should be typed in Times New Roman font size 12. citation standard ISO 690.

More details can be found at www.transportsciences.org.

TRANSACTIONS ON TRANSPORT SCIENCES

Volume 3 | 2010 | Number 4

CONTENTS