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Biomechanical Response of Head During Impact Loading

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ABSTRACT: The biomechanical response of the head during impact loading represents a globally highlighted issue associated mainly with passive vehicle safety.

Based on the detection of the dynamic values and biomaterial characteristics during the head impact loading are we able to observe the biomechanical response of biological structures to the loading. The internal mechanical response to the speed vector spreading in both extra- and subdural areas is discussed and its dependency on the characteristics of external mechanical loading. Mathematical and physical models were used for the computational tasks of inverse dynamics that allow the solving of interactional biomechanical conditions in both real and extrapolated extreme-loading situations. Based on the changes of input mechanical loading, i.e., the changes of static, dynamic, impulse and inertial loading, the appropriate biomechanical reaction was able to be determined and the value of the HIC (Head Injury Criterion) specified which can be approximately correlated to the AIS (Abbreviated Injury Scaled) using a table.

The knowledge gathered can be applied to all situations when a head hits an obstacle. The mechanisms relate well to the "injury" issues during both work and free time activities, such as transportation, sports, etc.

KEY WORDS: Biomechanics, head injury, impact, passive safety, head injury criterion.

1 INTRODUCTION

Head injuries are the most frequent threat to life. It is caused mostly by the strong impact of the head with some sort of obstacle. Looking at this issue from the point of view of most frequent brain injuries we can find that the foremost reason is traffic accidents (60-80%), including motorbike riders (10%) and pedestrians/bicycle riders (8-10%). The second most common reason is falls (10%). Approximately 9% of brain traumas are caused by assaults, sports, and shooting injuries. Less than 8% of cranial traumas come from industrial work, especially metallurgy, mining, construction, wood-processing, etc. (Juráň, et al., 2001).

From the very beginning biomechanics has been concerned with mechanical damage to the human body. The majority of attention has been centered on traffic and sports injuries. There have been many efforts to prevent such accidents. Primarily these efforts have focused on the most frequent causes of more severe head, chest and spine injuries. A mathematical-physical elastic-dynamical model has been devised based on the known facts which has allowed the observation of the head injury mechanism, i.e., during the impact. The model has

11 degrees of freedom and includes a skull, brain, spine, upper and lower limbs, and a torso fastened to a frame. We have further examined the behavior of the scalp, brain and velamen, both in humans and apes, and simulated it using the Maxwel-Kelvin model. The measurement was performed using implanted accelerometers and pressure meters on a human and ape head, and the results have been summarized in a system simulation by the means of a linear impedance model with two degrees of freedom. The area of injuries of the spine and its components was observed using a model consisting of three-component elements and thus simulating the whole spine. This simulation was further extended by the mechanical influences of the spinal flexors and extensors.

From the biomechanical point of view the human body can be conceived of as a closed mass system which can be simulated by a movable spatial system of objects. The structure consists of individual subsystems representing the body segments. After mastering a given motion situation the systems as the whole begin an interaction with their surroundings (Sychra, 1993)

External mechanical stress applied to a head can be divided in this manner:

1) Contact (i.e., the impact of the object with the head), further subdivided into:
   - Penetrating – the impacting object penetrates through the skull, usually causing impressive and compound fractures and other brain injuries – these are relatively rare during car accidents recently.
   - Non-penetrating – there is no penetration of objects or skull shards in the skull interior:
     - by static force – generates high tension, eventually deformation,
     - by dynamic force – in a very short time period (20-200 ms),
     - impulse injury – generates a shock wave, spreading further through the brain tissue (Kovanda, et al., 2000).

The type of external mechanical stress is decided from the size of an object’s contact area and also from the speed of the impact. Apart from fractures, there may be also contusions caused by contact mechanism. Usually these are located at the spot of impact, but can also be found at the opposite spot, according to the so-called *par contre-coup* mechanism.

2) Contactless, inertial – is caused by acceleration and deceleration, e.g., during the movement of the cervical spine (the origin of the so-called inertial injuries) (Juráň, et al., 2001).

External mechanical stress causes the internal mechanical response of various anatomical parts of the head. If the external stress exceeds the so-called injury tolerance level, defined for the body or its parts as the limit of the specified injury occurrance (Ommaya, et al., 1994), an internal mechanical response occurs. Various parts of the head may be affected by a wide scale of injury mechanisms.

The most frequent is a traumatic brain injury. The key to understanding the external stress which causes the injury is the internal mechanical response of the brain. This comes from an external mechanical impact, transported from the head’s skin to the brain threads via the skull. An inner mechanical response is affected by the strength and duration of the external mechanical impact. The strength has to be large enough for the injury-causing tension to affect the brain threads. In other words, some degree of tolerance has to be exceeded. The duration determines the manner and scale of the internal brain tension.

Short impacts can be defined as impacts which have a characteristic duration equal to the characteristic time of the head system’s own frequency. These impacts happen, for example, when shot (a bullet of small weight) hits a head with high speed. This particular case is also called a ballistic impact. An inner mechanical brain response is subsequently determined by the progression of generated waves. This means that a wave front, containing high or increasing tension, progresses through the brain tissue. This progression of the tension wave through the brain tissue has been considered to be important for the internal mechanical response for a long time and there are circumstances specified (Brands, 2002) under which the wave progression responsible for the internal mechanical response is given.

If a head is hit with a heavy object with a lower speed, an impact with longer duration occurs, and no wave front progression can be detected. Additionally, the response usually has a lower gradient. In slower impact conditions a quasi-static response occurs, during which the inertial effect can be omitted (Brands, 2002).

Two types of waves have been specified, spreading through the brain, based on the analytic use of linear viscous-elastic theory (Brands, 2002):

1) S-waves (shear waves) generated during longer duration impacts (e.g., car accident-related impacts) with a frequency between 25 and 300 Hz.
2) P-waves (compression waves) generated during short duration impacts like a ballistic impact. In this case the waves spreading through the brain have a frequency between 10 kHz and 3 MHz.

2 PROCESS LEADING TO HEAD INJURY

During physiological or extreme loading a series of events occurs, depending on the manner of the force, which implies the final biomechanical response of the organism (Figure 1). The great variability of the types of external mechanical loading prevents a simple description and simulation of a biomechanical reaction and internal mechanical response, which fundamentally affects the injury mechanism, on a physical model. The influence of the variability of the mechanical properties of soft and rigid tissues, as well as the influence of frequency and impulse loading of individual structures, plays a major role in determining an adequate biomechanical response (Brands, 2002).

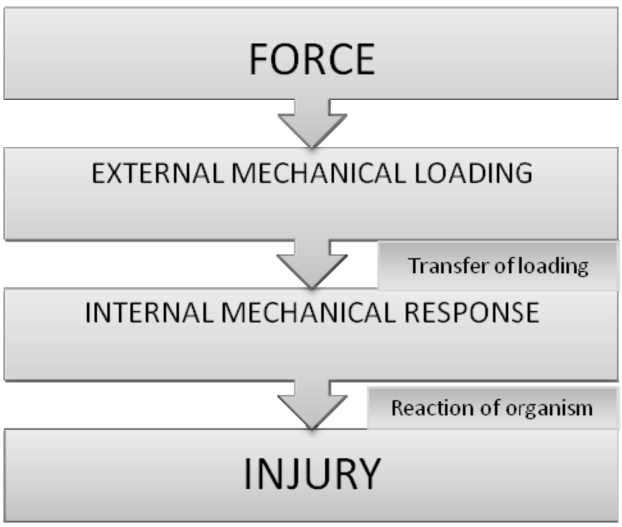


Figure 1: Process leading to head injury.

Taking this into consideration, it is crucial to specify individual internal mechanical responses based on external mechanical loading by testing physical models.

A biomechanical response is, in this case, represented especially by the speed and acceleration of individual head segments and tissue structures. These act as the source of the majority of biomechanical injury criteria, i.e., Head Injury Criterion, further along by the pressure distribution and the speed of the specific wave spreading, as well as its other properties (frequency, wave length). Head Injury Criterion (HIC) is defined as:

$$HIC = \left\{ (t_2 - t_1) \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right)^{2,5} \right\}_{max}$$

where:

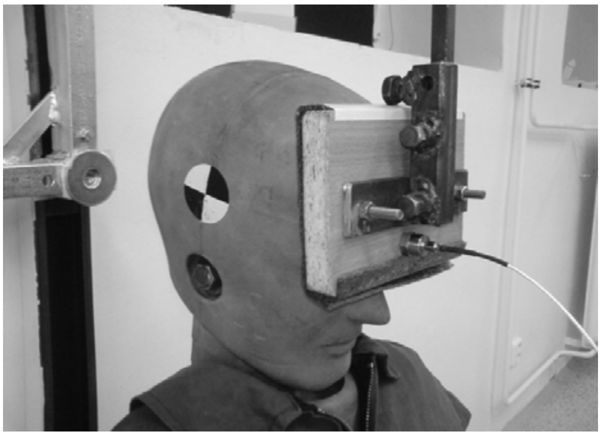
a(t) is the resulting value of head acceleration and t_1 and t_2 are the variable start and end times of the interval, in which the HIC reaches its maximum.

For the reason of regulation the maximum of t_1 a t_2 interval is set to 15 or 36 ms. For the consequences of frontal impact the HIC has been presented as a reasonable discriminator between serious and less serious injuries (Tarriere, 1981). It also correlates with a risk of skull fracture (Ran, et al., 1984).

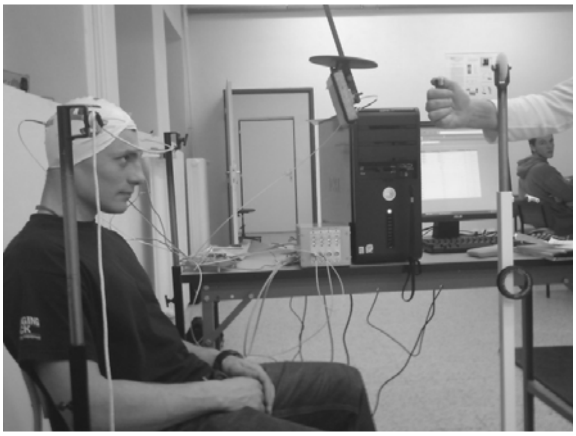
By testing and choosing an appropriate process of biomechanical response identification the reference values of biomechanical indicators are determined, based on measurements under standard physiological loading, and this data is correlated with values under extreme loading. At present there is no precise method specified for the detection of biomechanical indicators. Additionally, the threshold of organism tolerance to impact loading or head vibrations differs greatly among authors.

3 EXPERIMENT

The goal of the experiment was to simulate various characteristic external mechanical loading in laboratory conditions. This loading is represented by individual detectable internal mechanical responses. Based on the results of this experiment it is possible to evaluate a biomechanical response to extreme loading with greater precision and to better characterize the injury criterion and injuries possibly incurred.



The main detection method consists of scanning biomechanical reactions to external mechanical loading. Such a purpose is served by an impactor with the capability of force and impact rigidity regulation, which has been constructed in the BEZ laboratory at FTVS UK. Measuring took place on probands as well as a figurine ÚSMD Manikin, used by the Transportation faculty of ČVUT in Prague for compound impact tests, the so-called crash-tests. The impact blanket was equipped with a 2mm thick dampening foam for slowing the impact and also with an accelerometer for determining the primal impact. The tested person was seated on a regular school chair without a head support. The chair was secured against moving. The impact spot was the middle of os frontale at a slight forward bend. A three axis accelerometer was placed at the center of gravity of the figurine's head and a modified hat with one axis accelerometers was placed on the proband's head. Conditions were the same for the figurine and the probands. The mass of the weight and the impactor displacement were counted from the required values of the HIC before the actual experiment. To secure the displacement the impactor was fixed using fish line.



After over firing the fish line the gravitation force caused a motion and the predicted impact. All the data from the accelerometers were recorded by a computer and subsequently analyzed and correlated, and the output values verified. Thus the biomechanical response of a "living" head and a figurine head to an impact could be simultaneously compared.

6 measurements were performed (marked 001-006) for both probands and a figurine, using weights and displacements as seen in Figure 2. For clarification the results for the figurine are marked "D", for the first proband "O", and for the second proband "P".

Table 1:Weight and displacement.

Number of impact	001	002	003	004	005	006
Weight (N)	5	5	5	10	10	10
Displacement (m)	0,47	0,77	0,97	0,47	0,77	0,97

4 RESULTS

At the moment of impact with the head the impactor's speed sharply decreases, deceleration increases, the dampening foam is compressed, and the impactor transfers its energy, via the specific contact areas, to the head. Soft tissues are compressed and the skull is deformed. The head gains a large acceleration with approx. 2ms delay, which propagates dorsally. The motion is unevenly accelerated. After approx. 6ms the impactor's deceleration reaches its highest value and begins to decrease and stop. The acceleration of the head continues for 3 more milliseconds and at a particular moment that depends on the rigidity and strength of the impact, regarding violence timespan, it stops and starts to decrease. The oscillation is then strongly inhibited due to the neck muscles and also the properties of viscous-elastic materials complex of the skull and brain (Figure 2).

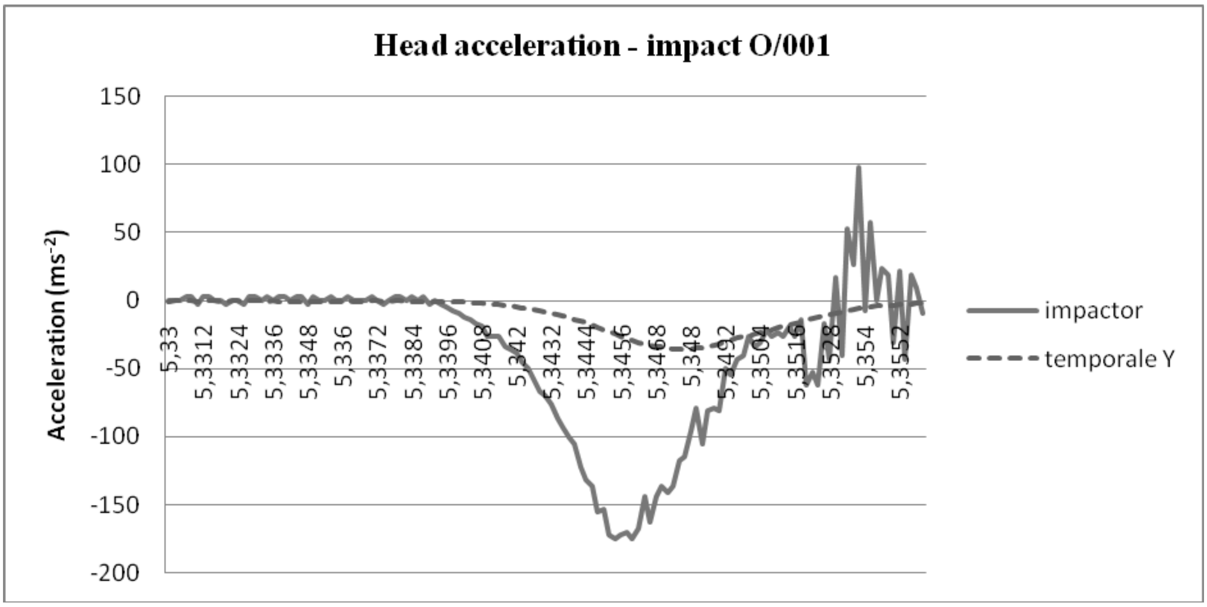


Figure 2: Head acceleration – impact O/001.

As can be observed with the figurine, shortly after the impact when the impactor's deceleration is still increasing the head is compressed in the anterodorsal direction and consequently expands along the Z axis. This ends at the moment when the impactor loses contact with the head, returns slightly and begins to oscillate. At this moment the acceleration is significantly increased along the X and Y axes. The X axis acceleration is caused mostly by a circular head movement around the rotation axis in the joint connection between the head and neck (Figure 3).

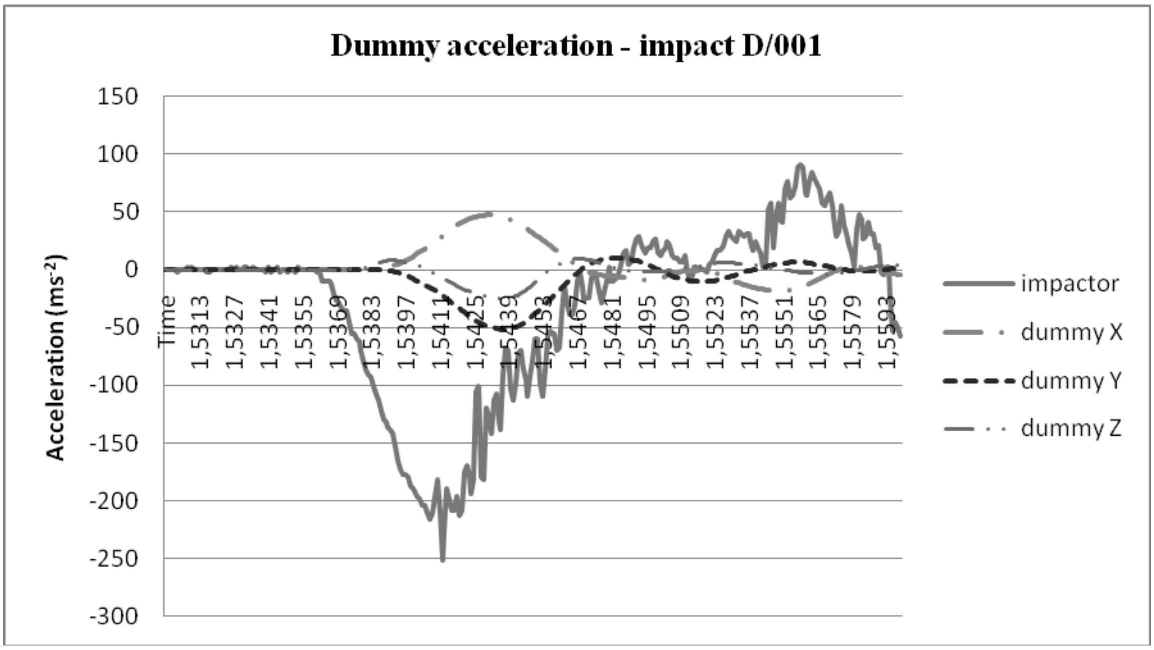


Figure 3: Dummy acceleration – impact D/001.

The head's movement after the impact is defined as damped oscillation. Environment resistance can be considered equal to the speed value. It is evident that the inhibition is much stronger with a "live" head than with the figurine's. The figurine's head oscillates around the medium value with a larger amplitude, much like an oscilloscope (Figure 4).

This is due to the figurine's construction where the head-neck joint is implemented as an elastic connection without an inhibitor. This fact is important for the evaluation of HIC for the figurine.

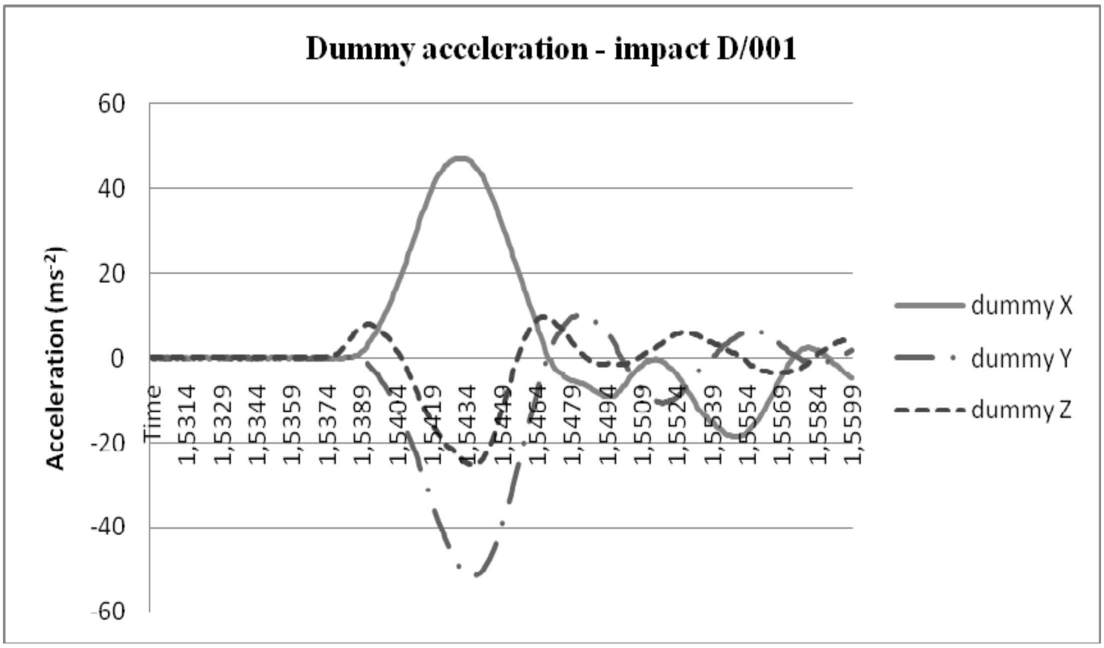


Figure 4: Dummy acceleration – impact D/001.

We will now concentrate on the increase in the "live" head acceleration depending on speed and strength of the impact (Figure 5, 6). A little displacement of the pendulum (measurements 001 and 004) resulted in a slow impact of the order of 10 ms with a regular acceleration increase and decrease. A medium displacement (002 and 005) accelerated both the increase and decrease of the acceleration to approx. 8 ms, while the inhibition is still smooth because of the inhibited aperiodic oscillation $b > \omega_0$, where b is an inhibition constant and ω_0 is a radial frequency of the oscillation itself. For the largest displacement (003 and 006) the time was shortened to approx. 6 ms and another wave in the inhibition was also noticed, as well as a slight short increase in the acceleration during deceleration. In this case the inhibition constant is lower than that of the radial frequency and of the oscillation $b < \omega_0$.

The impact was thus faster than the muscular activation (Horst, 2002). Similar plot shapes were reached for both probands with the only difference being for proband O, with the weight increased on the impactor, which meant a stronger impact, and an increased time to the maximum acceleration value, which was more significantly decreased.

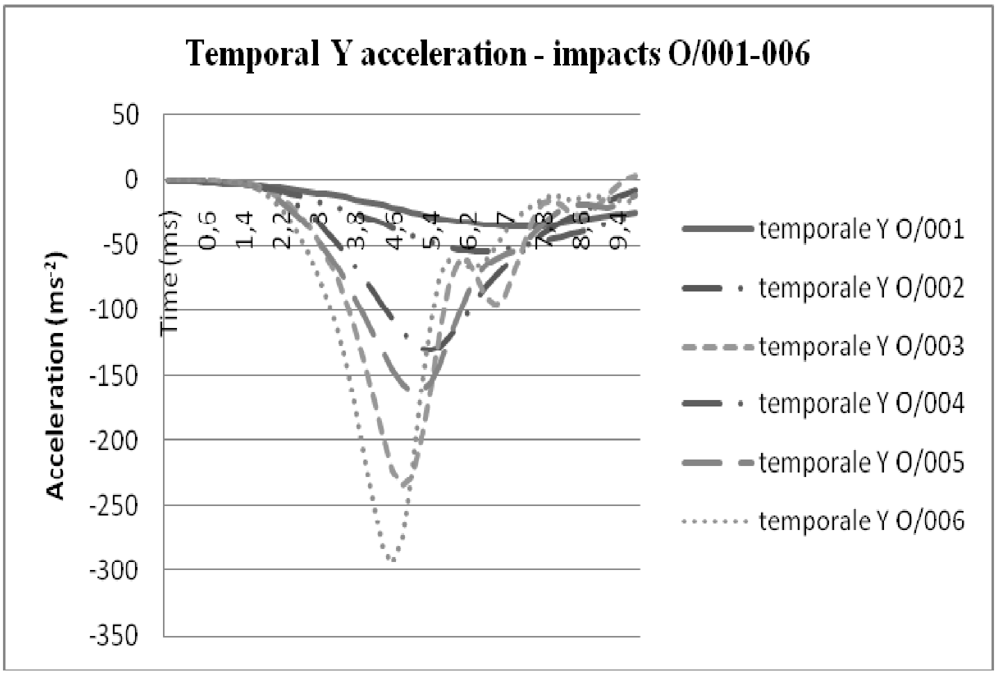


Figure 5 : Temporal Y acceleration – impacts O/001-006.

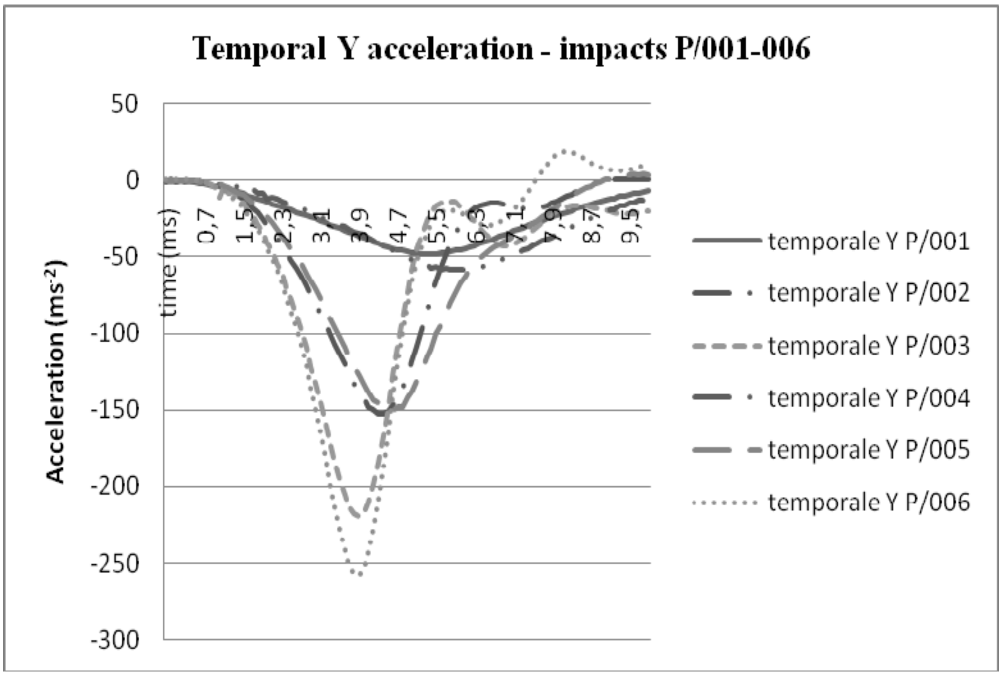


Figure 6: Temporal Y acceleration – impacts P/001-006.

No decrease in impact time depending on the impact strength could be seen for the figurine (Figure 7), only the maximum value of the acceleration increased and, as was mentioned, no significant inhibition $b \ll \omega_0$ occurred.

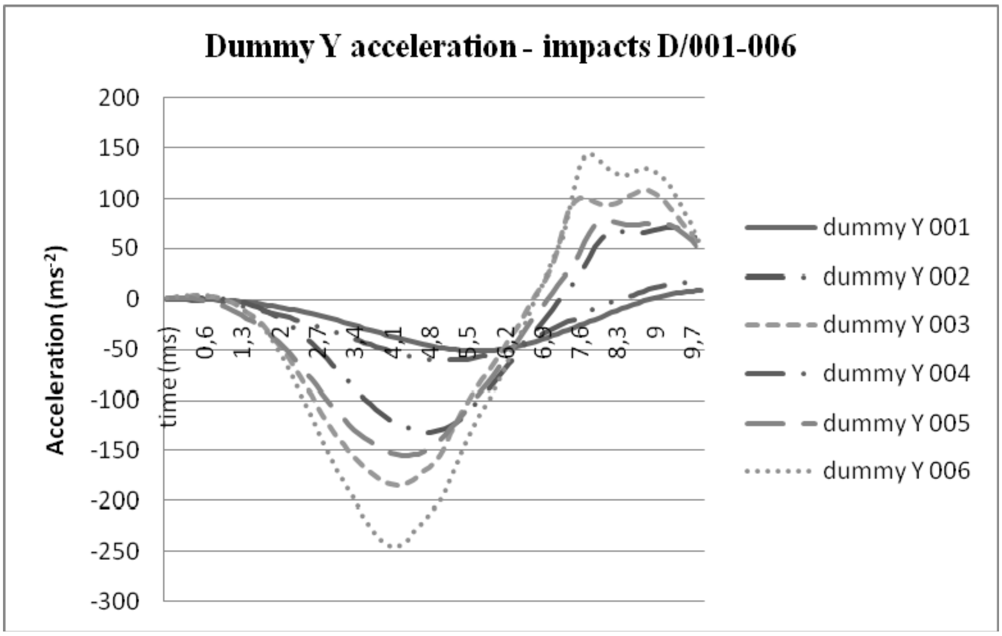


Figure 7: Dummy Y acceleration – impacts D/001-006.

In the next part we will compare "live" heads and a figurine head. With equal starting conditions the strength and course of the head acceleration are equal for both the figurine and "P" proband, while the "O" proband differs in every measurement mostly relating to the speed of increase and decrease of the acceleration (Figure 8-13). Both curves are much steeper. This may be caused by the rigidity of the skull, which is less elastic during the impact, but this is less likely than the different speed and efficiency of the neck muscles intervening. Proband O may be instinctively faster at resisting the impact using a significant involvement of neck muscles and thus making the impact seem harder and the response faster. However, according to the shock theory and the impact time this should have no particular influence either. The most likely explanation seems to be fastening the neck muscles resulting in a slightly different position of the cervical spine and the head, which was consequently loaded not only to bend, but also to buckle. This "resistance", however, looks counter-productive, as, from the subsequent evaluation of HIC, slightly higher values result than for proband P. The inhibition is for O/003(Figure 10) and O/006 (Figure 13) also specified by more significant oscillations that could lead, in my opinion, to par contre-coup injury. On the other hand, some higher resistance to whiplash syndrome could be expected.

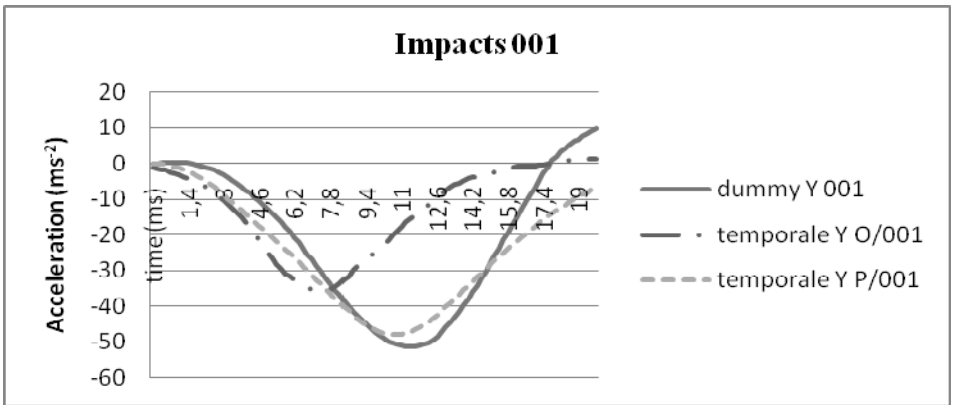


Figure 8: Acceleration – impacts 001.

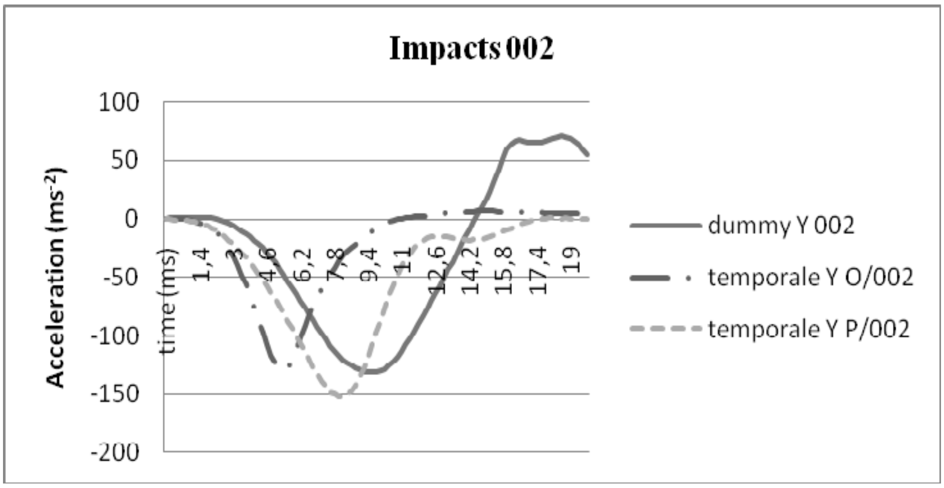


Figure 9: Acceleration – impacts 002.

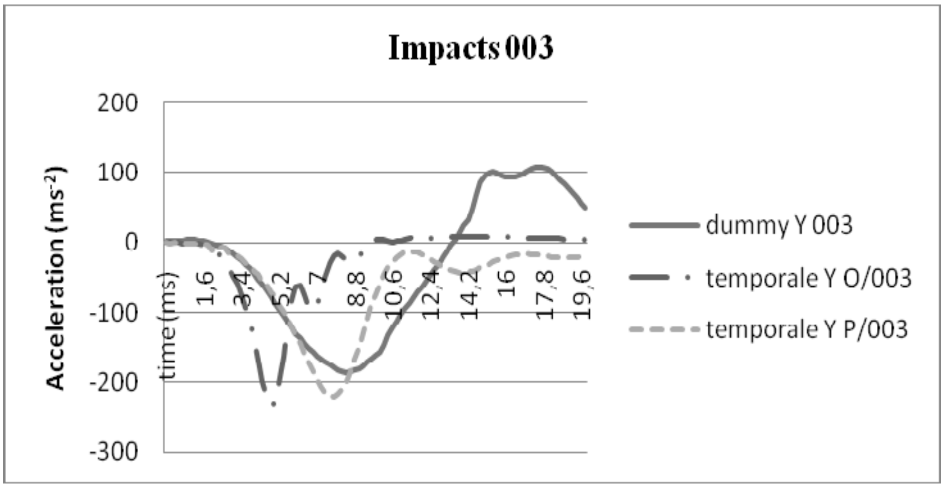


Figure 10: Acceleration – impacts 003.

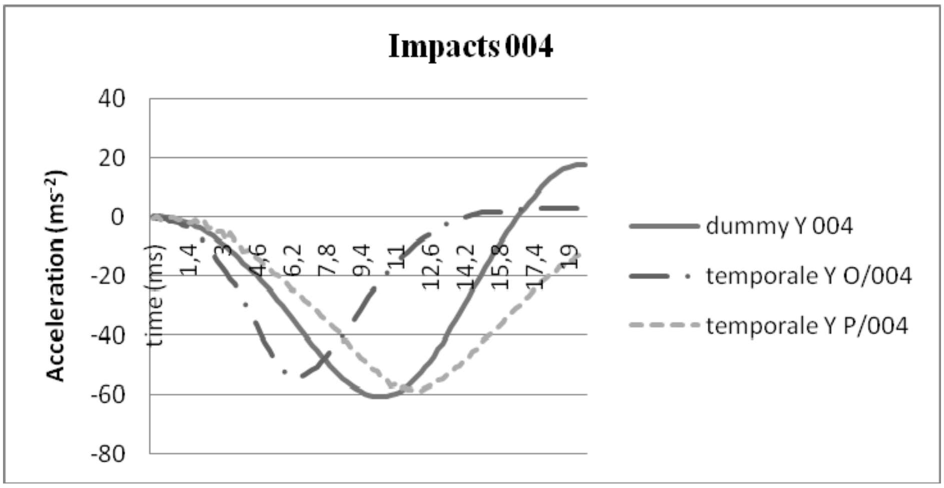


Figure 11: Acceleration – impacts 004.

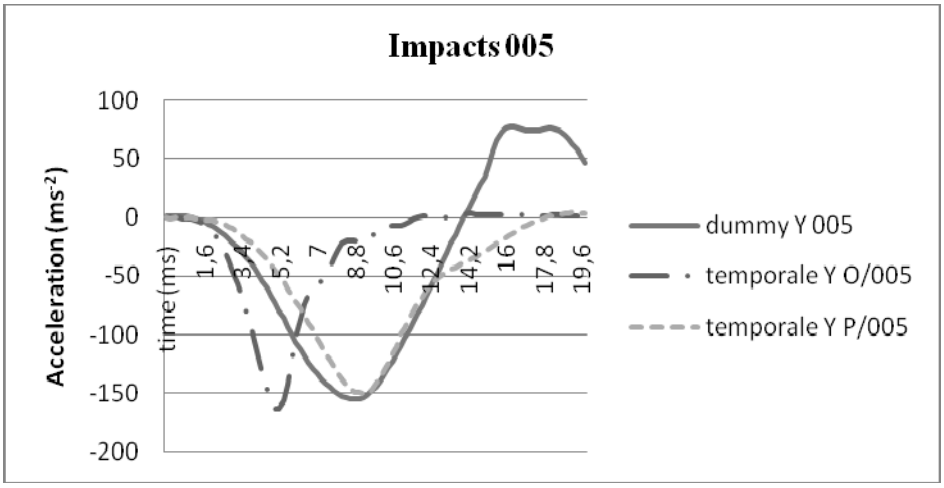


Figure 12: Acceleration – impacts 005.

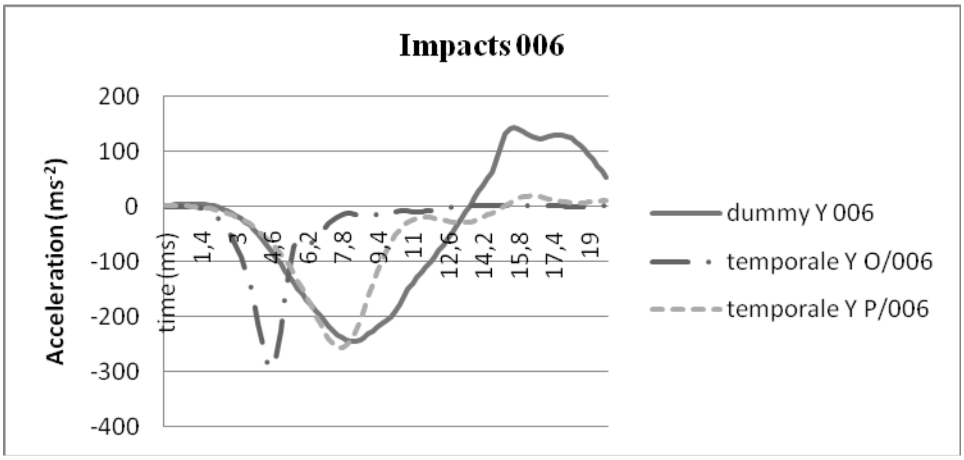


Figure 13: Acceleration – impacts 006.

If we now convert the obtained values using the equation:

$$HIC = \left\{(t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2,5}\right\}_{max}$$

and choose 15 ms as a time interval, considering the impact to be rigid, we can compare the risks of head injury for the test subjects and the figurine.

We can see similar values resulting for both probands (Table 2), even if they are slightly higher for O proband, which is caused by a faster acceleration increase as described above. For the figurine much higher values were attained, though. In the case of impact D/006 if the HIC value had been so high for a living person, it would have been exposed to a load causing lethal injuries. This is caused by a lack of inhibition for the figurine head compared to a "living" one as described above, and therefore its acceleration switches to opposite values instantly after the primary increase. Evaluating HIC for a shorted timespan and considering only the primary acceleration peak seems to be an appropriate solution. The HIC is then comparable to probands (Table 2, Figure 14, 15).

Table 2: Head Injury Criterion.

HIC	Tested O	Tested P	Dummy	Dummy – primary peak
/001	18,7	17,5	18,9	12,0
/002	97,3	72,8	304,6	65,4
/003	188,1	176,7	707,9	134,2
/004	36,2	27,3	36,3	17,8
/005	127,7	110,2	446,5	109,6
/006	215,4	185,1	1428,2	256,8

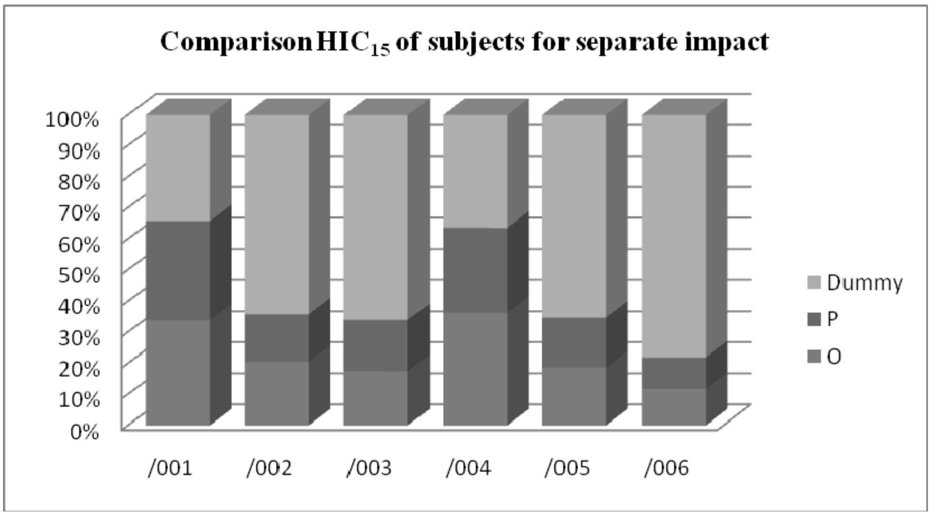


Figure 14: Comparison HIC_{15} of subjects for separate impact.

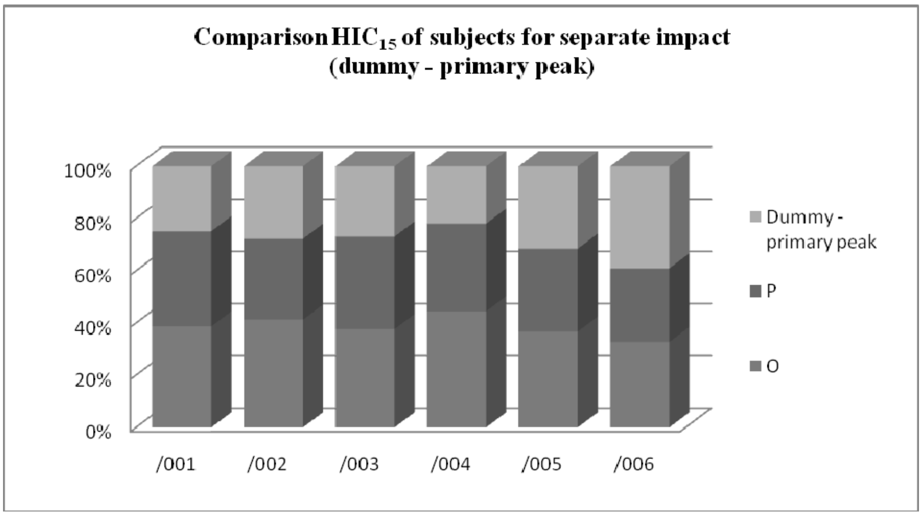


Figure 15: Comparison HIC_{15} of subjects for separate impact – dummy – primary peak.

5 CONCLUSION

Only Y axis acceleration was detected on probands during the experiment (i.e., in the direction of the impact). Regarding the resulting acceleration to be:

$$\bar{a} = \sqrt{a_x^{\ 2} + a_y^{\ 2} + a_z^{\ 2}}$$

and considering that $a_x << a_y$ and $a_z << a_y$, we may presume that $\bar{a} = \sqrt{a_y^{\ 2}}$.

If we take into account that EES (Energy Equivalent Speed) comes up to the strongest of tested impacts, than the highest measured HIC for a proband was 215, which corresponds to EES speed < 21 km/h (Fanta, 2009). According to the correlation of HIC and AIS we may presume a 95% probability of AIS 0.

The experiment confirmed the validity of an HIC and AIS correlation for low speed and strength of impact (HIC values about 200). For higher HIC values it would be necessary to simulate the whole situation using simulation software. This will be accomplished in future projects.

For a figurine and a short, rigid impact it is advisable to evaluate using only the primary acceleration peak.

ACKNOWLEDGEMENTS

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Modelling of Price Demand Elasticity for Entry to Bus Terminals

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ABSTRACT: This article deals with the modelling of price demand elasticity for entry to bus terminals. The model was applied to a specific bus terminal – CBT Prague Florenc (the abbreviation CBT stands for Central bus terminal).

KEY WORDS: Demand elasticity, price demand elasticity coefficient, linear regressive model, distant and influential observation, bus terminal.

1 INTRODUCTION

Demand elasticity represents an important mix of information that can be used by a company's management to aim their marketing efforts when acquiring new customers, i.e., bus carriers, and gathering information about corresponding customer/potential customer reactions to their price offers. Changes in pricing can be used to determine additional bus carriers or revenues that can be achieved by changing price policy. From the demand and elasticity theory results that calculating and estimating reactions in demand for entering bus terminal based on changes in pricing can be used both a relative coefficient price elasticity $e_{x,y}$ calculus in each observed demand values and corresponding fees for arrival charges, or calculating coefficients of price elasticity e_P with the help of linear model.

2 PRICE ELASTICITY OF DEMAND IN ENTERING BUS TERMINAL MODELLING

Price elasticity of demand in entering bus terminal has been applied to an example of CBT Prague Florenc bus terminal.

2.1 Calculating coefficients of price elasticity of demand in entering bus terminal CBT Prague Florenc

The price elasticity effect represents a corresponding reaction of the bus carrier on changes in arrival fees by the bus terminal CBT Prague Florenc operator ČSAD Prague holding corp. (ČSAD is the national bus carrier.)

The indicator of this change is the coefficient of price elasticity e_P that can be expressed by a formula:

$$e_P = \frac{y_1 - y_0}{(y_1 + y_0)/2} : \frac{x_1 - x_0}{(x_1 + x_0)/2}$$

Where y_1 is demand at the new price, y_0 is demand at the current price, x_1 is the new price and x_0 is the current price.

The coefficient of price elasticity can be expressed as a fraction of the percentage change in the amount of demand and the percentage changes of prices. According to the values that e_P can gain we can determine demand dependence on price:

1. Elastic, when e_P < 1, i.e., a decline in the arrival fee of 1% causes a demand rise of more than 1%, assuming constant incomes of bus carriers and constant arrival fee of other bus terminal operators, revenues of bus terminal operators rise, amount of outlays by bus carriers declines, fee-demand function is declining and has got a negative order.
2. Unit elastic, when e_P = 1, i.e., the demand percentage change equals the fee percentage change with the opposite sign, revenues of bus terminal operators do not change as well as the outlays of bus carriers assuming constant incomes of bus carriers and constant arrival fees of other bus terminal operators, the function can be graphically shown as a hyperbola, the order of the price demand function equals zero.
3. Inelastic when e_P > 1, i.e., the demand percentage change is lower than the fee percentage change, the drop in the arrival fee invokes a drop in the terminal operator's revenues assuming constant incomes of bus carriers and constant arrival fees of other bus terminal operators, rise in outlays of bus carriers, order of the price demand function is positive.

Because the amount of demand goes in the opposite direction than the fee rise (a rise in fees leads to a decline in demand and also the other way round), the price elasticity demand is negative.

Statistical data for calculating price elasticity is partly data from CBT Prague Florenc bus terminal operator ČSAD Prague holding corp. and partly expert estimates. Arrival fee development at CBT Prague Florenc bus terminal from the years 2002 to 2006 is stated in table 1. We used a weighted average to calculate the average arrival fee. Weights for different bus lines are stated in table 2, since 2006 all bus lines originating in Slovakia have been a part of international bus lines. Because of the low amount of data and the small differences between arrival fees in given years it was not possible to carry out a linear regression and coefficient calculation for each bus line operating at the bus terminal CBT Prague Florenc, i.e., international lines, domestic lines, and lines originating in Slovakia, however, the average arrival fees have been calculated for each year. Price elasticity coefficients in table 3 have been calculated accordingly to the e_P formula.

Table 1: CBT Prague Florenc – Arrival fees.

Year	2002	2003	2004	2005	2006
Arrival fees [CZK]:					
Domestic lines	250	250	260	260	275
International lines	600	620	630	630	650
Slovakia lines	480	500	540	540	0
Average price (weighted average)	360.50	366.30	362.90	362	368.75

Table 2: CBT Prague Florenc – Weights

Year	2002	2003	2004	2005	2006
Weights for:					
Domestic lines	65%	65%	70%	70%	75%
International lines	25%	24%	21%	20%	25%
Slovakia lines	10%	11%	9%	10%	-

Table 3: CBT Prague Florenc – Price elasticity coefficients

Year	2002	2003	2004	2005	2006
Total number of check out buses	194 000	227 000	228 000	230 000	220 000
Average price of arrival feel [CZK]	360.50	366.50	362.90	360.00	365.75
Price elasticity coefficients	-	9.82	-0.47	-3.25	-2.41

3 LINEAR REGRESSION – RESULTS

3.1 Example 1 – with distant and influential observation

Linear regression was at first carried out for the years from 2002 through 2006, i.e., for n = 5 including distant and influential observation – year 2002. Regression results have proved that this point must be excluded from the data file. The final linear model formula determined by regression analyses using Microsoft Excel achieved the following form:

$$Y = - 410634.2 + 1731.5. X$$

The final formula cannot be considered to be a linear model describing the relation between the total number of processed buses and the average arrival fee price at CBT Prague Florenc bus terminal. The data reliability is 46% and therefore we cannot state the statistically important relation between the number of processed buses and the arrival fee price. The inefficiency of this model is also confirmed by the correlation coefficient value $r = 0.3907903$ that hints at the model's weak dependence between variables. The determination coefficient is $r^2 = 0.152717$, and this is a descriptive convenience measure to use a regressive formula for predicting. The determination coefficient can have a value between 0 and 1, a value close to 0 hints that the regression formula is not suitable for predicting. The normal error of estimation is 15843.66. The results of our testing show the inapplicableness of the regression linear model in this case.

3.2 Example 2 – without distant and influential observation – Model to support price measure decision making

Linear regression has been carried out for the years 2003 to 2006, i.e., n = 4. The final linear model formula determined by regression analyses using Microsoft Excel achieved the following form:

$$Y = 694188.7 – 1282.1. X$$

The final formula can be considered to be a linear model describing the relation between the total number of processed buses and the average arrival fee price at CBT Prague Florenc bus terminal. The estimated reliability is 92%. On a significance level 0.05 we have accepted the zero hypothesis H_0 (H_0: there is not a dependence between the arrival fee price and the number of processed buses, the alternative hypothesis is H_A: there is a dependence between the arrival fee price and the number of processed buses) but we reject the zero hypothesis on the significance level 0.1. This regression example is an extreme one, however, since at a significance level of 0.08 we may or may not accept the zero hypothesis. Statistically, a hypothesis up to 10% is acceptable, but unreliable, i.e., we cannot exclude the dependence between variables. Dependency between variables is confirmed on a significant level of 5%. If we accept the zero hypothesis then there is no dependence between the arrival fee price and the number of processed buses, which would express the position of CBT Prague Florenc bus terminal operator ČSAD Prague holding corp., which determines prices and has a monopoly on the bus terminal operator market in Prague. Bus carriers that want to enter Prague city center have no other choice but use CBT Prague Florenc bus terminal. If we decline H_0 then there is a dependence between variables and there will be a statistically significant relation between the arrival fee price and the number of processed buses. The correlation coefficient value r = –0.919043 hints at a strong dependence of the model between variables. The determination coefficient r^2 = 0.84464 is a value close to 1, and therefore the regression formula is usable for predicting. The normal error of estimation is 2099.60. The relative elastic model coefficient $e_{x,y}$ can be determined after forming the formula:

$$e_{x,y} = \hat{b} \cdot \frac{\bar{x}}{\bar{y}}$$

Where $\bar{x}, \bar{y}$ are the average values $\hat{b}$.

$$e_{x,y} = -1282{,}1 \cdot \frac{\bar{x}}{\bar{y}} = -2{,}07$$

Remark: Relative elasticity coefficient value is defined as a relative demand change caused by a relative factor change taking effect on demand.

As the value of the relative elasticity coefficient equals –2.07 and as this value is therefore lower than –1, this demand is elastic. This means that if there is a change in the arrival fee of 1%, the demand of bus carriers changes by 2% on average.

4 CONCLUSION

The second example of demand price elasticity concerning arrivals at CBT Prague Florenc can be labelled as a “Model supporting decision making in fee pricing” and the bus terminal operator can accordingly determine the reaction of bus carriers on changes in arrival fees. It can be said that if bus terminal operator increase the arrival fee by 10%, demand declines by 20% on average. However, revenues of the bus operator can remain the same or can even rise; this has to be calculated ad hoc by the terminal operator. That said, terminal operators can, with the price rise, also focus on a wider portfolio of services for bus carriers, improve the quality of the provided services, and offer longer terminal time slots that would help them retain or increase current revenues.

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An Application for the Impendance Spectroscopy Method and Building Material Testing

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ABSTRACT: The impedance spectroscopy is used to draw information concerning electrical properties of liquids and solids. Its principles can be used easily to advantage without any prior knowledge of electrochemistry. To apply the impedance spectroscopy method at the Physics Department, Faculty of Civil Engineering, TU Brno, the method had to be adapted to the laboratory environment conditions. Furthermore, a dedicated software had to be created for this method-based diagnostics. The author of this paper has created an application called IS_alpha, which meets these requirements. Measurements employing this application are fast and convenient.

KEY WORDS: Impedance spectroscopy, solid state, measurement automation, Agilent 33220A generator, Agilent 54645A double-channel oscilloscope, IS_alpha software.

1 INTRODUCTION

Most testing methods being applied in civil engineering research at present are of a destructive character. These methods feature a significant drawback related to the damage the material or structure unavoidably suffers during the test: they can be applied to a particular material, unit or component only once. Non-destructive testing methods (NDTs) are free of this limitation, this being their indisputable advantage. On the other hand, their exploitation in testing laboratories, as well as in practice, still remains at a very low level. Therefore, NDT methods constitute a significant component of today's building research.

Acoustic NDT methods, such as **acoustic emission (AE)**, **Impact-Echo (IE)** and **ultrasonic spectroscopy (USS)** make up the subject of research and development most frequently. Whereas the acoustic emission method is applicable to homogeneous materials under load, the Impact-Echo and ultrasonic spectroscopic methods apply to the materials which are free of load. All acoustic methods are based on the phenomenon of acoustic wave propagation in materials. It is to be noted that new electric testing methods, particularly the **electromagnetic emission (EMG)** method, have emerged recently which take advantage of the electromagnetic signal generation accompanying the formation and development of cracks in a material in the course of its time-dependent or climatic load or an external force action.

The present paper aims at contributing to the development of non-destructive testing methods in the building material testing field. It is our intention to present and investigate a new NDT method which has not yet been published in building industry periodicals, namely, the **impedance spectroscopy (IS)** method. The method is based on the measurement and analysis of electrical impedance characteristics of the building material under investigation. The essence of the mentioned method consists of analyzing the dielectric losses versus frequency plots. The method is applicable to the testing of low-electrical-conductivity building materials, such as plastics, glasses, ceramics, cements, aggregates, and a number of other materials. We will show that this method is fast-operating and its results are easily reproducible. On the other hand, this method shows some applicability restrictions. It cannot be applied to thick materials ($d > 1$ cm) and/or to other than low-electrical-conductivity materials. Although the method has already been investigated and published to a large extent in other branches, such as biophysics and electrochemistry, its research is at its very beginning in the building industry. It is for this reason, for the time being, we would rather consider it to be a supplementary method, to be combined with other well established and better-examined NDT methods. The research of this method should no doubt be continued, with the aim of discovering more relations between the material structure and its electric response.

Measurement automation and instrumentation design and implementation, which are focused on a particular method, have proved to be a must for any experimenter since the advent of experimental physics computerization. Thanks to the instrumentation manufacturers' efforts aimed at reaching compatibility with the present-time computer operating systems, automated measurements are easier to realize. This applies not only to the impedance spectroscopy method but also to other methods using available measuring instruments. In this way, the measurements are becoming faster and less exacting for the experimenter.

The impedance spectroscopy (IS) method has been designed to investigate the electrical properties of materials featuring various electrical conductivity values. Its principles have been described elsewhere [1][2]. At the Department of Physics, Faculty of Civil Engineering, TU Brno, the IS-based measurements have been implemented using the following instrumentation: Agilent 33220A generator, Agilent 54645A double-channel oscilloscope, HP 82350 PCI HP-IB Interface card, and a PC. To operate the above-mentioned instruments and to process the IS data acquired, software called IS_alpha has been prepared by the author of this paper.

2 EXPERIMENT SETUP DESCRIPTION

The instruments listed above are interconnected by means of GPIB (IEEE-488) cables and connected to the Type 82350 PCI HP-IB Interface card (or any equivalent type), which is plugged into a computer running WIN XP (or higher) operating system.

Agilent 33220A generator: frequency range, 20 μHz to 20 MHz (for sine wave output), the output waveform can be set within certain limits, the current setting being shown in the built-in LCD display. All settings can be made either using a numerical keyboard or by a rotary knob. Any setting changes take effect immediately. It can also be used to generate amplitude, frequency and impulse modulated output voltages. It can also be operated via GPIB, USB and LAN interfaces, providing compatibility with SCPI (VISA) (standard commands for program operated instruments).

Agilent 54645A double-channel oscilloscope: This is a general-purpose A/D oscilloscope featuring a bandwidth of 100 MHz, a sampling rate of 200 MSa/s, an internal memory of 1 MB for each channel. Its vertical sensitivity ranges from 1 mV/div to 5 V/div, for an input impedance of 1 MΩ (~13 pF). It is operated via an IEEE-488 interface through a built-in auxiliary module, HP 54657A. Display modes available: Averaging – when smoothing, the arithmetic mean is calculated from 200 successive values to be saved in the memory; this is the running average-based smoothing. In the normal mode operation, only 4000 out of one million randomly selected samples are displayed. In this case, narrow pulses may happen not to be displayed with a slowly-running oscilloscope time-base setting at all. For example, a 50 ns impulse could be captured and displayed by as many as 10 samples (200 MSa/s = 5 ns/sample). When a high-speed time base is used, the segment to be displayed consists of several short segments ("triggers"). The smoothing mode is used when the sampling rate (200 MSa/s) exceeds that of the sample saving rate in the display memory. For example, if the TB rate > 2 ns/d, several samples are merged by averaging into a single one to reach a better trace definition on the screen. Time base ranges: 2 ns/div to 50 s/div. Resolution: up to 50 ps. Autoscale mode - enabled for >10 mVp-p, searching in 20 ms intervals.

PC-plug-in Agilent 82350 PCI HP-IB Interface card: This is a standard high-speed card, featuring an IEEE488 serial interface, a built-in buffer. It is compatible with the SICL (Standard Instrument Control Library) and VISA IO (Virtual Instrument Software Architecture) libraries for Windows 98/ME/NT/2000/XP.

3 DESCRIPTION OF THE INSTRUMENT OPERATION AND DATA PROCESSING APPLICATION

IS_alpha is a software which has been designed to operate measuring instruments and process IS data. The program has been written in C++ programming language. Agilent company proprietary VISA libraries have been used when preparing the program. For the application to run smoothly, PCI-GPIB card drivers must be installed first. The application must be run under WIN XP or higher OSs. The user can run other applications without restrictions.

After the application is started, links are checked and the oscilloscope and generator are powered ON. If the above check is successful, the operator will be faced with a user-friendly environment, Fig. 1., with of course no data acquired at this stage.

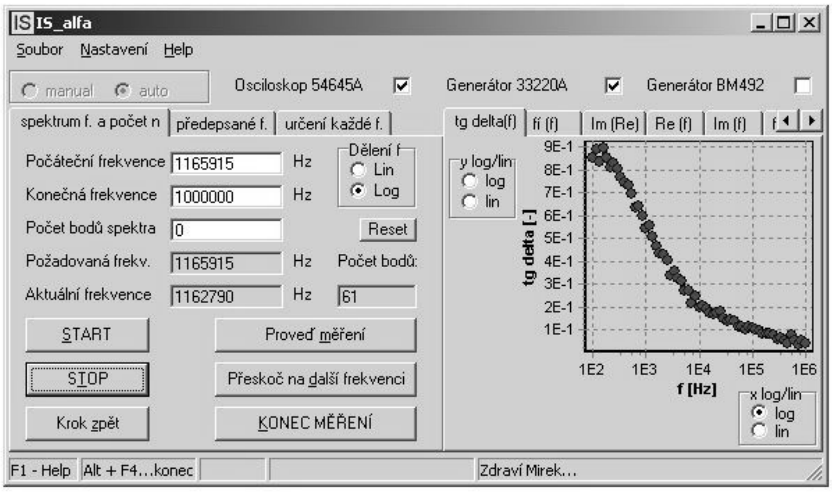

Figure 1: Alpha_IS application program interface.

The application "remembers" the settings made last time before the application was closed. The operator may therefore run their measurements immediately. Prior to quitting, they will be alerted by a sound signal. To modify the adjustable parameters, an easy-to-use "menu" can be employed whose submenu item called "File" provides an option to cancel the acquired data and initiate new measurements, save the measured and processed data, and, finally, close the application correctly. The submenu item called "Setting" can be used to change the addresses (IEEE-488) at which the system instruments are logged in.

As a further option, the following quantities can be entered: the maximum voltage of the signal voltage source and the maximum measuring sample count, the frequency spectrum to be used for characterization, the required oscilloscope B-channel input resistance and capacitance, the Agilent generator output rms voltage, the current measurement run name (code) to be used automatically while saving the data, measurement accuracy improvement or acceleration measures to be taken, such as the measurement repetition number for each spectrum point and the measurement time separation. The last "menu" item is "Help", the meaning of which being obvious. The next line shows the Agilent instruments being used. An option for manual operation of the sine wave generator can be clicked here. In this case, the application instructs the operator in how to navigate through the measurement sequences, thus carrying out a slow semi-automatic measurement. It is apparent from Fig. 1 that the application allows the user to select the initial and end frequencies, the spectrum point count and the spectrum frequency distribution: linear or logarithmic. The operator is informed continuously of the measurement status during the measurement process. This is shown in the left-hand-side part of the IS_alpha application window. The right-hand-side provides previews of the tgδ(f), φ(f), Im(Re), Re(f), Im(f) plots, and, in the last tab, the measured data (frequency, phase, P). (Key to the diagram symbols and parameters – see [2][3][4].)

In addition to viewing the frequency data generated (1st tab in the window left-hand-side), the operator can also use default values for their measurements (2nd tab, Fig 2) or set the frequencies individually (3rd tab, Fig. 3).

Provided the measurement has been successfully completed, the operator sets the measured data save operation on target location. The application will create the following files at the selected location:

name__date_time_year_tandelta_f.epw; name__date_time_year_im_f.epw; name__date_time_year_im_re.epw; name__date_time_year_re_f.epw,

which can be opened immediately in the Easy Plot graphic editor. The last file having been created is *name__date_time_year.mir*, in which all measured data are written in text form, to be presented in the IS_alpha right-hand-side window. This file is ready to be processed by other dedicated applications, e.g., transforming selected data for use in modeling S/W applications.

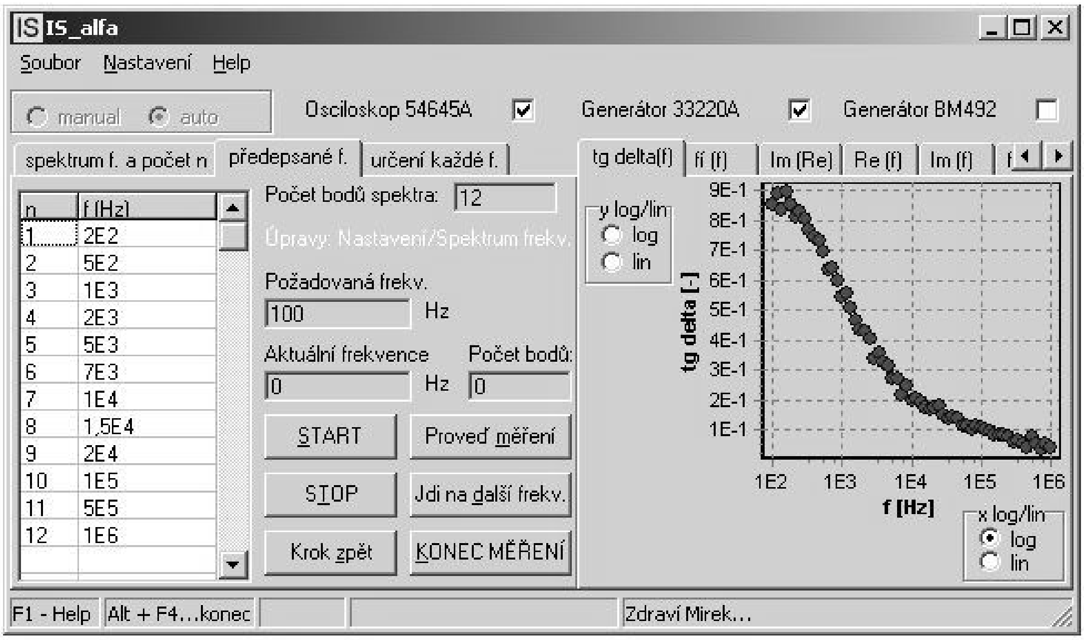

Figure2: Other options of IS_alpha-based measurements.

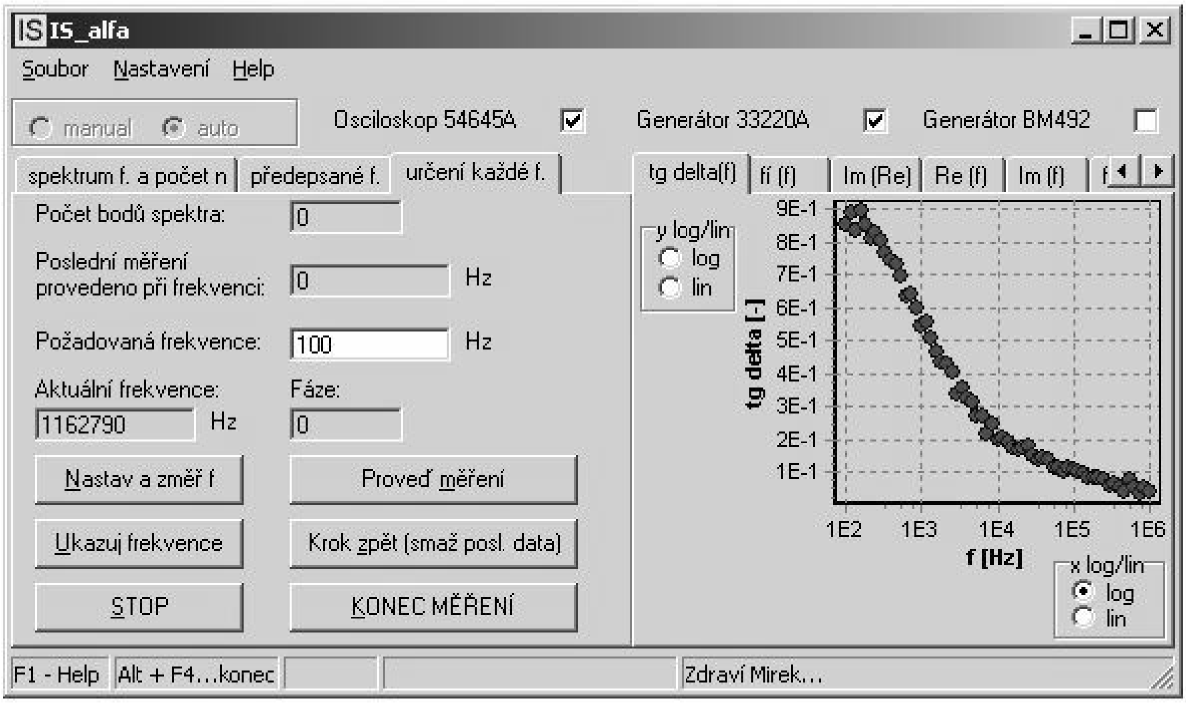

Figure3: Entering the different spectrum frequencies – the operator´s panel.

4 CONCLUSION

The IS_alpha application meets the requirements for an IS method based automated measurement specialization. Such a specialized mode of usage can also be seen as a disadvantage. Nevertheless, its application appears to be more than adequate in the laboratory environment conditions of the Physics Department, Faculty of Civil Engineering. The measurement results achieved by means of the above application operating the IS method are presented elsewhere in these Proceedings.

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Methods of Safety Estimation in Road Traffic with Taking Pedestrian Traffic Problems into Consideration

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ABSTRACT: In this paper basic data are presented which characterise the state of road traffic safety in Poland, and methods of road traffic safety danger estimation are characterised.

KEY WORDS: transport, pedestrian, safety, methods of estimation safety danger.

1 INTRODUCTION

From earliest times, factors determining the spatial form and transportation system of the first clusters of human, then cities, were human physical abilities (pedestrian), enabling it to change the place of residence and to travel distances. Designing city buildings and road networks was guided by the pedestrians' safety and convenience. For example, Leonardo da Vinci created a project of a city where pedestrian and vehicular traffic were separated, which, according to him, would insure optimal conditions for both ways of traffic. With the design of the first vehicle and the development of motorisation the situation began to change. Cities formed for the safety and convenience of pedestrians didn't match the needs of the increasing number of cars which required more space. Although the development of motorisation undoubtedly brought both social and economic advantages, it also caused many negative events, among others adding to environmental pollution, noise, direct human health risks and life hazards. Cars "forced" pedestrians to be on pavements and brought about the necessity of using the many road signs and light signals which determine the method of road traffic.

2 THE NATIONAL PROGRAM OF ROAD TRAFFIC SAFETY - „GAMBIT 2005"

The increasing number of vehicles which are travelling on roads has caused the worsening condition of road traffic safety. About half million people die every year in the world. In Poland in 2007 49 536 [1] road accidents occurred, in which 5 583 people died and 63 224 were injured.

Taking road traffic safety into consideration ministries accepted and started to realise the National Traffic Road Safety Program - "**Gambit 2005**" at a cabinet meeting on 19th April 2005. In this program has aims for the next few years. The main purpose of the program is in **decreasing the number of victims by over 50% for 2013 in relation to 2003**.

The main purpose of the National Traffic Road Safety Program "**Gambit 2005**" would be able to be realised possibly due to the realisation of the following partial aims [4,5,8]:

- ***Purpose 1***: Creating a basis to conduct efficient and long-term activities for road traffic safety.
- ***Purpose 2***: Forming a safe attitude of road traffic participants.
- ***Purpose 3***: Pedestrians, children and cyclists protection.
- ***Purpose 4***: Creating and keeping a safe road infrastructure.
- ***Purpose 5***: Decreasing the seriousness and consequences of road accidents.

To realise the purposes of the "***Gambit 2005"*** program it is necessary to take into account designing proper programs and set of guidelines which determine the rules of all functioning subjects in road traffic. These programs should allow for all essential parameters which decide about transport process realization. For this reason it is necessary to recognize the reasons, circumstances and accidents effects to efficiently prevent or ease their consequences. The essential task helpful in the proposed realization of ***"Gambit 2005"*** is estimating road traffic safety.

3 SAFETY ESTIMATION IN ROAD TRAFFIC

The essence of road traffic safety is the un-conflicted participation in road traffic of all its participants [1,2]. The aim of research into road traffic safety is the analysis of the **HUMAN-VEHICLE-ROAD system** (and its environment), specifying the possible use of its improvement and effects estimation which result from its research.

In research of road traffic safety most attention is often paid to the systematic and quantitative description of the road traffic safety state.

This can be achieved by:

- statistical specifications;
- statistical indicators;
- regressive dependences;
- operative safe indicators.

The effects of this kind of research are statistical specifications, which present number dependences of road accidents from such features as: accident victim (female/male sex, age group, type of accident result), accident place (in the sense of the kind of road net segment, e.g., junction, straight road section, pedestrian crossing, etc.), kind of vehicle – accident participant, kind of accident (head-on collision, running into, vehicle overturning, etc.), manoeuvre during which accident happened, accident causes, and other accident circumstances [1,2]. On the basis of the achieved results it is difficult to determine the real reason for the road accident.

In connection with this it is essential to work out during the analysis of danger in road traffic the answers to the question: who or what is the reason for the danger in road traffic.

All research agree in admitting that the main role is the "human factor" (driver or pedestrian) in generating accidents dangers [2,7]. Those works come down to first of all determining the connection of the increasing situation of danger in traffic with human physiological parameters.

Another branch of research contains works whose aim is in determining the connection of the roads with road accidents. Those works are conducted in two ways which are possible to separate:

- analysis of dangerous places on roads (the so called problem of "black spots"),
- analysis of the influence of road elements on the level of road accidents.

Research of road influence and traffic conditions on creating a danger to safety in road traffic is most often expressed in the analysis of the influence of road geometric elements on accident levels and in the analysis of dangerous places on roads or its segments.

When discussing the range of road traffic research from a quantitative assessment (which characterizes traffic safety) point of view it is necessary to mention road traffic modelling.

It is interesting to first of all identify motion model parameters which can be helpful in the estimation of its safety. From existing foreign and national literature traffic models there are not many which consider the aspect of traffic safety with pedestrian traffic specifically or in which the verification criteria is traffic safety [2].

Estimation of an accident's danger state is made on the basis of proper indices. For it to be measurable an estimation is considered, e.g., accidents number index (possibly fatalities and injured) per 10 thousand people, 10 thousand cars, or 1 million kilometre-vehicles, danger index, and accident seriousness. The danger index is a synthetic index which considers the intensity of road traffic and the linear density of accidents on road sections. An accident seriousness index estimates the connection of mortalities per 100 accidents occurring.

On the basis of the presented material it can be seen that the measures are not useful for the estimation of pedestrian traffic quality on the area, due to the big variability of parameters, even for the traffic participant.

It can be observed that on the basis of the above mentioned indicators it is difficult to estimate pedestrians' safety in road traffic, because the existing indices relate to the general number of road accidents, vehicles or transport work. Besides, the absolute numbers of dead and injured do not give sufficient information about the danger levels at particular points, possibly on the whole transport network of the city. Such an attitude to danger level estimation testifies that the estimation of road traffic safety level is effectively done due to vehicle traffic and avoiding pedestrian traffic, which is an inseparable part of road traffic.

Another essential problem in road traffic safety analyses (including pedestrians) is a source of information about events in road traffic. From the available literature information on events in road traffic can be received from:

- analysis of road accident statistics,
- analysis of conflict situations,
- analysis of before conflict situations (states),
- analysis of simulation methods effects.

One of the basic problems in road traffic safety research is a deficit of information which allows for a safety analysis by ex ante methods. The basic source of information about events in road traffic is the statistics of road accidents. The main disadvantages of such a kind of information source are the following:

- road accidents are relatively seldom events,
- road accidents give ex post information, what is equal to road traffic victims,
- number of accidents in a specified place is usually small,
- accidents occur in some time interval (sometimes large) and are not comparable because of change in traffic conditions,
- those data are not sufficiently exact (not precisely filled in "cards of road accident"),
- information attained this way allows an event to be placed in a fault category, not the reasons for the accident. The most important advantage of that information source is that thanks to the attained statistics it is possible to observe a general tendency and methods of accident situation development.

The first step on the way to before-accidents analysis is a method of conflict situation in road traffic analysis (Traffic Conflicts Techniques TCT) [1,2,7]. Conflicts technique is used in the estimation of road traffic safety in many countries. The main advantage of this method is a bigger frequency of the conflict situation occurring in road traffic (can be up to 10 times the frequency of road accidents). By using techniques of traffic conflicts can be said about security risks in the stages immediately preceding traffic accident, which often occurs as a not result to take, by the road users, various types of emergency actions (turn, brake, change the speed of traffic).

Necessary information about danger state and its level lend themselves to methods which use before-conflicts state analysis (without the necessity of waiting for road accident or conflict situations). Quantitative analysis of the danger in before-conflict states is possible thanks to using so-called behavioural danger indicators (BIZ). BIZ are potentially dangerous faults of traffic participants or time and space dimensions which indicate the danger state of road traffic safety.

Those values are an effect of the behavior of the traffic system **C-P-D** in determined traffic – road conditions. By using BIZ the safety danger can be studied in normal traffic – road situations where objective traffic safety danger occurs, but it is accepted or invisible to the traffic participants. The frequency of these occurring before conflict situations is larger than just conflict situations because of the permanent presence of safety danger in road traffic.

Analysis of danger in road traffic using the traffic conflicts techniques method and by using behavioural indicators of danger allow a danger situation estimation in ex ante type road traffic.

Another essential problem in traffic safety research is pointing dangerous places. Pointing dangerous places is made on the basis of generally available information about road events, road, traffic parameters, and thanks to using proper indices. Information about each road event, apart from for registry purposes, can be divided into the following groups:

a. general data about the road event - date and place of event, kind of event and its effects (e.g., human victims);

b. circumstances and causes of the event – behaviour of traffic participants (driver, edestrian), road information, lighting and weather conditions;

c. detailed information about the place of the event – functional identification, technique parameters, organisation and traffic steering and other features of the event location connected with it;

d. information about traffic at the event location – traffic intensity, quality and direction structure, speed of vehicles stream and intensity of pedestrian traffic;

e. detailed information about traffic participants and vehicle – age, sex, driving licence category, type and make of a car, etc.

Locating dangerous places is also a component element of the general analysis traffic safety state. The purpose of locating dangerous places and also their analysis is recognising reasons for the events occurring in the place. Determining the reasons allow a project to e arried out and improvements to traffic safety (traffic quality) to be made.

Safety estimations (dangers) in road traffic (and also pedestrian traffic) are made most often on the basis of road accidents statistics. Data from road accident cards do not give answers for many of the questions of the accident’s circumstances. Detailed and reliable information can be provided only through scrupulous research, thanks to which it would be possible to determine the complicated and various reasons for the accidents. As each road accident has its typical, often repeatable circumstances, successful analysis of road traffic safety danger (and also pedestrian traffic) requires information about the event condition: place, time, traffic conditions (intensity of pedestrian and vehicular traffic, size of kinetic vehicles stream) and reason for the accident. Road accidents can be treated as disturbances in functioning of the system: **HUMAN - VEHICLE - ROAD**.

An estimation of road traffic safety (also from pedestrian point of view) shouldn’t only be boiled down to an analysis of the statistics of road accidents, because on that basis it is difficult to define and estimate the factors which influence rising road accidents and their effects. It is therefore necessary to have different types of undertakings which help with determining the proper methods for estimating the level of road traffic safety. This especially concerns standardizing the range of means and research methods.

Proper realization of the activities which follow road traffic safety improvement (and also pedestrians’ safety) and achieving the essential economic effects requires the use of proper diagnostic methods. Those methods should allow danger estimation of different accident types (e.g., vehicle-pedestrian type) and simultaneously give indispensable information about dangerous places and the reasons for the accidents rising in those places.

4 CONCLUSIONS

From the presented analysis of road traffic safety it follows definitively that the pedestrian traffic problem does not have the correct place in those considerations. In principle separate analysis and danger estimation from a pedestrian point of view are not made. The importance of these matters is only signalled on the occasion of a general analysis of road traffic safety. This is unfortunately the wrong method as accidents with pedestrians involve too many victims (dead and injured).

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Acceptance of Train Delays by Passengers

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ABSTRACT: The article deals with an analysis of a final evaluation of a survey among passengers which aimed at defining a subjective rate of delay acceptance by passengers and disorder of the mass public transport system's connections in cases of delays.

KEY WORDS: Public transport, railway traffic, delay, passenger survey.

1 CONTEXT AND SIGNIFICANCE OF THE SUBJECT OF INQUIRY

A substantial characteristic of Mass Public Transport (MPT) is the ensuring of changing relations between its individual lines (of the same or different types of transport or carriers). The issue of the interlinking of MPT lines in the stages of traffic schedules preparation in the Czech Republic has already been sufficiently mastered. However, the principles for the operational solving of links to delayed services during operational exceptionalities are not so clear.

For each expected stopover, one of the following situations may arise in the case of a delay:

1) Schedule of linked services will be kept strictly. This means that the delay will not be transferred onto other services with a positive impact on both passengers in linked services and carriers. On the other hand, a linked service will be disappeared, leading to the longer waiting of transferring passengers.

2) A set waiting time of linked services will be followed. This will lead to a generation of delays in the linked services with a possibility of the avalanche spreading throughout the whole public transportation network, but passengers will regard the MPT (or Integrated Transport System – ITS, respectively) system as reliable – they will assume that they will, in most cases, get to their destination with just a slight delay.

The above described possibilities both have their advantages and disadvantages and in every case a certain group of passengers is impaired. A universal decision on the correctness of a variant (at the assembly of schedules or during the operative traffic control) does not exist – it depends on particular cases. Unfortunately, a request from the side of MPT contractors (Ministry of Transport, regions), or ITS organizers respectively, inclines more and more towards not waiting for delayed services. As a consequence of an effort to increase the attractiveness of MPT, and also, among others, to minimize the total commercial time in MPT means of transport, the MPT contractors try to shorten the time necessary for transfers between MPT lines. Nevertheless, if there is a delay, it automatically leads to an increase in the probability of the occurrence of the negative impacts of such a situation. For this reason, the authors try to elaborate on a method for the optimum solving of operating particularities in transfers between MPT means of transport, especially between trains.

2 OBJECTIVE HARM SUFFERED BY PASSENGERS BY THE DELAY OF A SERVICE

In each transfer link whose maintaining is threatened by the delay of a service with which a transfer is planned, the interests of two groups of passengers come into conflict. On the one hand, there will be a significant harm suffered by the passengers waiting at the transfer point in the transport vehicle for the delayed service, as well as by passengers getting in the delayed service at wayside stations ("departing" group). On the other hand, harm is caused to passengers arriving at the stopover station in the delayed service ("arriving" group) and a loss of a connecting service for them means another (usually significant – according to the interval and the number of further transfers) increase in the delay to their destination.

In order to compare both described cases, the authors proposed a value which, in its nature, represents the total time loss for passengers from one or the other group (Jacura & Týfa, 2007). This is calculated for both groups of passengers as a multiple of the waiting time and a total of the multiples of the numbers of persons travelling for the same total travelling time, and a coefficient of the sensitivity of a passenger towards the delay – see formula (1).

$$F = t_w \cdot \sum_{(j)} P_j \cdot c_j \qquad (1)$$

where:

F – harm suffered by passengers due to delay [persons·min]

P_j – number of persons in group j, travelling for same travelling time [persons]

t_w – waiting time (explained further in greater detail) [min]

c_j – coefficient of sensitivity of group j passenger on delay [-]: $0 < c_j < 1$

The coefficient of sensitivity towards delay c was introduced into the formula because the authors assume that the subjective negative perception of a delay by a passenger depends mainly on his/her total travelling time. In the practical usage of the described mathematical formula it can be expected that personnel of a carrier will, in the case of an occurrence of an exceptional situation, be able to estimate the waiting time, number of passengers and the route of their travel (and so, also the commercial time), but coefficient c must already be known before the emergence of such a situation. A hypothesis was formed (Jacura & Týfa, 2007) that the tolerance of a passenger for the length of delay C rises with the travel time by the so-called logistic function (S-curve) – see formula (2).

In order for the substitution of a level of tolerance into the function of harm suffered by passengers due to delay F to correspond with the logic of the reality (function F reaches higher values, the more negative the impact is on passengers due to delay) it is necessary to carry out a conversion from the value level of tolerance to a variable of the coefficient of sensitivity of passengers according to formula (3).

$$C = \frac{q}{1 + b_0 \cdot b_1^{t_{tot}}} \tag{2}$$

$$c = 1 - C \tag{3}$$

where:

C – [-]: $0 < C < 1$

c – coefficient of sensitivity of a passenger on delay [-]: $0 < c < 1$

q – higher asymptote of logistic function [-]: $q = 1$

b_0 – parameter of logistic function [-]: $b_0 > 1$

b_1 – parameter of logistic function [-]: $0 < b_1 < 1$

t_{tot} – total passenger's commercial time [min]

Determination of both unknown parameters of the logistic functions b_0 and b_1 is possible only on the basis of a regressive analysis of the results of a survey among passengers. Therefore, the authors made a survey involving train passengers in the Czech Republic and Slovak Republic whose main output was the behaviours of regressive logistic functions for three different cases of delay. Readers will be acquainted with the procedure and the results of the search of parameters b_0 and b_1 in chapter 3.

2.1 Limit waiting time

When determining limit waiting time for which, from the point of view of harm to a passenger, it pays to wait at a transfer point for a delayed service, the authors draw on the comparison of function F in two extreme cases. The first extreme situation occurs if a connecting service never waits at a transfer point. In such a case, passengers on the service arriving to the transfer point ("arriving" group) will have to wait for the next service of the connecting line for time t_w, which is equal to the line (or track, as case may be) interval of the connecting MPT line deceased by the delay, that is, time remaining to the regular departure of the next connecting service. The second extreme case happens if a connecting service always waits for the arrival of the service to which it is linked. In such a case, the "departing" group is impaired and the waiting time t_w represents the time of delay of the service for which the connecting service waits at the transfer point which the passengers of this group must spend in excess in the MPT means of transport.

A more detailed form of formula (1) thus corresponds to formulas (4) and (5).

$$F_{ar} = (i - t_{del}) \cdot \sum_{(j)} P_j \cdot c_j \tag{4}$$

$$F_{dep} = t_{del} \cdot \sum_{(k)} P_k \cdot c_k \tag{5}$$

where:

F_{ar} – harm inflicted upon “arriving” group of passengers [persons·min]

F_{dep} – harm inflicted upon “departing” group of passengers [persons·min]

i – line interval of connecting line (or track interval) [min]

t_{del} – time of delay [min]: $t_{del} < i$

The limit time of delay is, therefore, calculated from the equation of the right sides of formulas (4) and (5), and gains the form of formula (6):

$$t_{del,\lim} = \frac{\sum_{(j)} P_j \cdot c_j}{\sum_{(j)} P_j \cdot c_j + \sum_{(k)} P_k \cdot c_k} \cdot i \qquad (6)$$

where: $t_{del,lim}$ – limit time of delay [min]

Formula (6) can be interpreted in such a way that the limit time of delay is a part of a connecting line interval which equals the proportion of reduced numbers of passengers (number of passengers multiplied by the coefficient of sensitivity of passengers on delay) “arriving” from the total number of passengers on both services (i.e., both the “arriving” and “departing”).

3 PASSENGER SURVEY AND ITS EVALUATION

The passenger survey was carried out from 2nd July 2008 to 11th January 2009 through a form placed on the website of the project (http://stanice.fd.cvut.cz) and also in June and July 2009 through oral questioning at railway stations and stops in Prague and around the city.

3.1 Questionnaire content

In the first part of the survey, data are collected from a respondent about one route selected by him/her where he/she goes by train. The data collected from this part of the survey are used mainly as explanatory variables for regression and correlation analyses (Řezánková, 2007). The inquiries include a selected travel route, its commercial time (subsequently corrected according to the schedule), purpose and frequency. Question five asks for the number of transfers a passenger must make on a selected route during regular operation.

Question six, beginning the second part of the survey, asks the respondent about the amount of time saving necessary in transport on his/her route for he/ she to be willing to transfer regularly one more time due to this. Question seven probes the limit frequencies of varying delays on a given route that still do not deter a passenger from a further journey. Similarly, question eight investigates the highest tolerated delay on arrival to a destination due to a missed connecting train. Similarly, question nine tries to trace the level of acceptance of a delay in the case of a passenger sitting in a train waiting for a delayed service. The last, third part of the survey concentrates on respondent’s personal data (year of birth and sex) if respondents are willing to provide them.

The aim of this article is not to acquaint the reader with complete results of the survey among the travelling public, but merely with an assessment of the parameters of the level of passengers´ tolerance of the delay function.

3.2 Calculation of regressive logistic function

As stated in chapter 2, the main aim of the passenger survey is the assessment of constants of the logistic function (2), which should determine the level of the passengers´ tolerance of the delay. Since the logistic function’s parameters are not linear, it is not possible during the general determining of all three constants q, b_0 and b_1 by means of regressive analysis to use an unequivocal method of the least squares. But, because in our particular case we have the defined value $q = 1$ (see above) in advance, by gradual modification of formulas (7)–(9), whose key part is linearizing logaritmization, the authors came to the substitution (10), by which the logistic function transforms into the linear function (11). As is standard, first the values of the parameters B_0 and B_1 are determined by the method of the least squares and the values of the constants b_0 and b_1 are determined by reverse substitution.

$$\boldsymbol{C} = \frac{1}{1 + b_0 \cdot b_1^{t_{tot}}} \tag{7}$$

$$\frac{1}{C} - 1 = b_0 \cdot b_1^{t_{tot}} \tag{8}$$

$$\log\left(\frac{1}{C} - 1\right) = \log b_0 + t_{tot} \cdot \log b_1 \tag{9}$$

$$\textbf{\textit{SUBST.:}}\ C' = \log\left(\frac{1}{C} - 1\right)\textbf{;}\ B_0 = \log b_0\ \textbf{;}\ B_1 = \log b_1 \tag{10}$$

$$\boldsymbol{C' = B_0 + B_1 \cdot T_{TOT}} \tag{11}$$

Quality of the detected regressive logistic function was evaluated mainly by the determination index I^2. Another parameter used for determination of the expressive value of the regression function is the mean square error of estimation (*MSE*), which confirms a better regression function the closer it drops to zero. Also, for each regression a so-called F-test of dispersion analysis was carried out on the suitability of the created model (quality test of balancing points by a regression curve. The test zero hypothesis claims that the calculated regression function has no real predicative value. (Hindls, 2004)

3.3 Results of the regression of tolerance of delay to commercial time

A total of 404 passengers participated in the survey, 78 % of whom filled in the internet version of the questionnaire.

The results of the regression analysis, including its quality characteristics, can be found in table 1 and figures 2 and 3. The markings in table 1 correspond to markings in chapters 3.2. Quantile F-division with 1 and 404-1-1 = 402 degrees of freedom $F_{0.95}[1; 402] = 3.865$, and so it is possible, at the level of significance of 5 % in all cases, to reject the zero hypothesis of an unsuitable regression model. In figures 2 and 3, points describe the calculated values of C_i, the strong curve represents the determined regression logistic curve with parameters according to table 1.

Table 1: Characteristics of the regression logistic function of the level of tolerance of delay to total commercial time.

q. no.	delay characteristics	b_0	b_1	I^2 [%]	*MSE*	statistics *F*	rejection H_0
7	delay in destination	11.530	0.993	39.68	0.032	204.587	yes
8	missed connecting train	236.592	0.987	35.03	0.060	121.640	yes
9	waiting for connecting train	31.912	0.989	54.99	0.030	365.680	yes

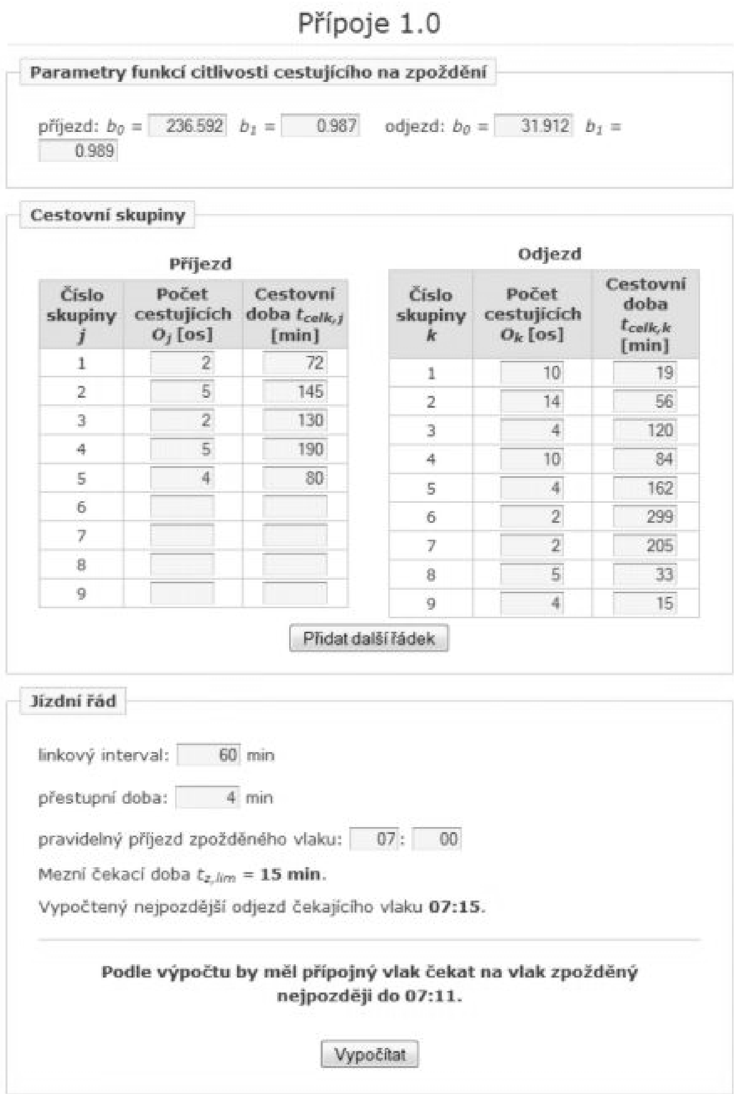
The sensitivity during waiting for a connecting train seems to be the best explanation, even though its determination index exceeds the 50 % limit only slightly. Relations in the remaining two cases were not explained so well by regression but, despite this fact, they give us at least a general idea of the relation trend.

3.4 Practical use of the methodology

For a practical use of the methodology described in this report an internet application "Přípoje 1.0" (Connections 1.0) was created. It can be used free of charge anytime by accessing the internet site of the project (*http://stanice.fd.cvut.cz*). The application is aimed at supporting the decision-making about the optimal waiting time for the delayed connecting train in the public transport change node. A demonstration of the application's functionality will be described later using a hypothetical sample.

According to the timetable, a train (thereinafter "the first train") arrives at the station at 7:00 with a connecting train (thereinafter "the second train") leaving the station at 7:10. The transfer time between these trains is 4 minutes. The line interval relative to the second train is 60 minutes. If there is a possibility for the dispatcher to influence the waiting time of the second train in the case that the first train is delayed and there is a will or an obligation to consider the time loss of the passengers in both trains, the dispatcher, with the help of the train personnel, will have the passengers' routes in both trains gathered, where in the first train only passengers changing for the second train are considered. For practical use inserting an exact route of every passenger would be very slow in many cases, therefore it is possible to group similar routes. Gathering information about the target destinations of the passengers and its forwarding to the dispatcher for the purpose of setting the waiting time of the connecting trains is already being done using mobile phones.

After that, the relevant worker (dispatcher, traffic controller) assigns a total travelling time (i.e., not only from the change node to the target destination) to each of the passengers´ routes according to the timetable, using his own knowledge or suitable software (IDOS). The number of the passengers and their total travelling time from both the delayed first train ("arrival group") and the connecting second train ("departure group") are then inserted in the "Přípoje 1.0" (Connections 1.0) form by a responsible dispatcher. The line or route interval of the second train is also to be inserted, i.e., at what time the next suitable train departs with the same route stopping at the same stations. For the routine use of the described application it would be suitable to be directly connected to an application for the total travelling time computation, as manual calculation consumes too much time.



parametry funkcí citlivosti cestujícího na zpoždění - **passenger sensitivity to delay function parameters**

příjezd – **arrival**

odjezd – **departure**

cestovní skupiny – **travelling groups**

číslo skupiny – **group number**

počet cestujících – **passengers number**

cestovní doba – **travelling time**

přidat další řádek – **add a new row**

jízdní řád – **timetable**

linkový interval – **line interval**

přestupní doba – **transfer time**

pravidelný příjezd zpožděného vlaku – **the late train schedule arrival**

mezní čekací doba – **limit waiting time**

vypočtený nejpozdější odjezd čekajícího vlaku – **computed latest departure of the second train**

podle výpočtu by měl přípojný vlak čekat na vlak zpožděný nejpozději do… – **according to the calculation the connecting train should wait for the delayed train no longer than until...**

vypočítat - **compute**

Translation:

Figure 1: Layout of the "Přípoje 1.0" (Connections 1.0) internet application.

A layout of the Connections 1.0 application, including the inserted and later computed data according to the sample above, is shown in figure 1. When adding groups of passengers with different travelling times any number of these groups can be added – by pressing the "Přidat další řádek" (add a new row) button. The quantities description corresponds to the relations in the chapter 2. The parameter values of the logistic functions b_0 and b_1 are filled in automatically but can be changed anytime, e.g., according to the own findings of the personnel. After pressing the "Vypočítat" (compute) button the user of the online application acquires the limiting delay time of the first train $t_{del,lim}$. If the scheduled arrival of the first train, the scheduled departure of the second train, and the transfer time between these trains are inserted, an exact time corresponding to the computed delay time is also displayed.

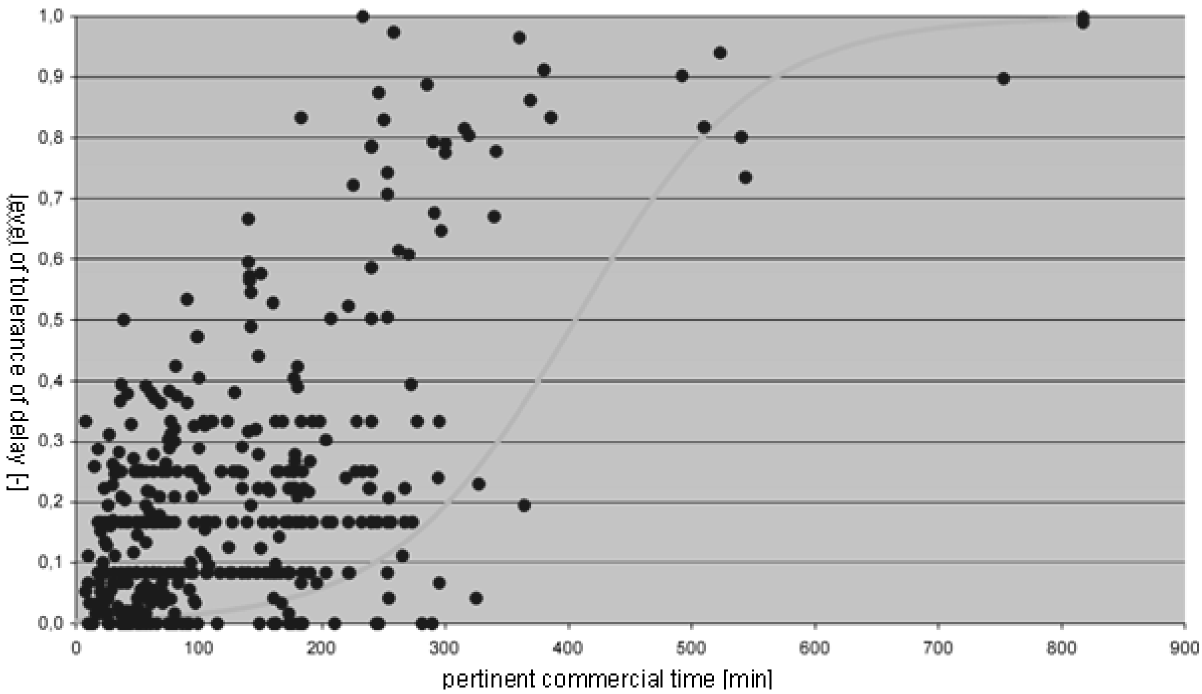


Figure 2: Level of passengers tolerance of delay to total commercial time in the case of a missed connecting train.

Considering the sample data used in the example above the limiting delay time of the first train where it is still worth the second train waiting for its arrival is 15 minutes. If the transfer time between the trains is subtracted from this value then the second train should wait for the arrival of the first train no longer than until 7:11.

4 CONCLUSION

A solution to connecting relations in MPT during the delays of individual services in the Czech Republic gains more and more importance in relation with the development of ITS and interval long-distance railway traffic. Deciding whether to wait or not for a service in the case of its delay can be aided by the method described in this paper.

The procedure described above takes into account only the subjective feelings of the passengers regarding their time loss and only in the two trains in between a connection. A delay transfer over the whole net and the operation needs must therefore be taken into consideration and so the described algorithm must be understood only as one of decision features. Consequently, a maximum waiting time restriction must be given in the General Timetable Appendix, which would set the limit where the passengers´ sensitivity to the delay is no more concerned. Nevertheless, the currently used waiting times are considered insufficient by the authors of this report.

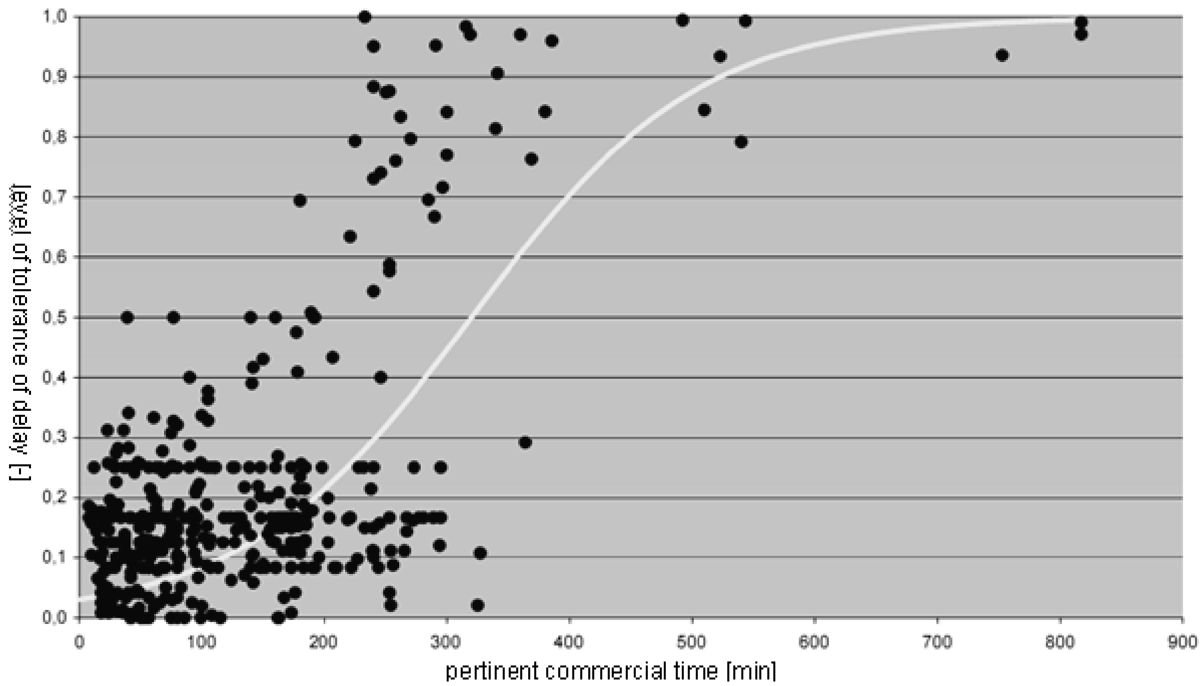


Figure 3: Level of passengers tolerance of delay to total commercial time in the case of waiting for a connecting train.

The methodology can be used during the designing of the General Timetable, where transfer traffic currents can be estimated with the help of a regular survey of the carrier and, based on this data, waiting times between the connecting trains can be set regarding the optimal transport services of the region and the public transport lines interlacing.

Even though the predicative ability of the created regression functions and the respondents sample are not ideal because the determination index does not near 100 % (however, other regression quality parameters are positive), according to the authors it is possible to use the survey results and specify them in greater detail in future on other occasions, as case may be.

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