DOI: 10.21062/mft.2022.024  http://www.journalmt.com

# Kinematic Analysis and Head Injury Criterion in a Pedestrian Collision with a Tram at the Speed of 10 and 20 km.h$^{-1}$

Ondřej Fanta (ORCID ID: 0000-0001-9978-9221)[1,3], Frantisek Lopot (ORCID ID: 0000-0001-9955-0261)[1], Petr Kubový (ORCID ID: 0000-0001-7634-2910)[1], Karel Jelen (ORCID ID: 0000-0002-8151-9810)[1], Dita Hylmarová (ORCID ID: 0000-0002-7791-4332)[1], Martin Svoboda (ORCID ID: 0000-0002-7344-1531)[2]
[1]Faculty of Physical Education and Sport, Charles University. José Mártího 31, 162 00 Praha 6 – Veleslavín. Czech Republic. E-mails: fantao@seznam.cz, lopot@ftvs.cuni.cz, kubovy.petr@seznam.cz, jelen@ftvs.cuni.cz, dita.hylmarova@gmail.com
[2]Faculty of Mechanical Engineering, Jan Evangelista Purkyně University in Ústí nad Labem. Pasteurova 3334/7, 400 01 Ústí nad Labem. Czech Republic. E-mail: martin.svoboda@ujep.cz
[3]Výzkumný Ústav Železniční, a.s. Novodvorská 1698, 142 01 Praha 4. Czech Republic. E-mail: fantao@seznam.cz
Tel.: +420 602 693 309

**The issue of accident analysis in relation to railway vehicles of urban mass transportation is highly accentuated at the moment. In terms of designing the frontal area of trams, adequate attention should be paid to the optimal front end design in order to reduce the risk of pedestrian injury. The properly used shape and materials can minimize the consequences of the pedestrian's contact with the vehicle, or the eventual dragging of the pedestrian under the vehicle. For the front end to be tested and optimized, it is necessary to develop and validate a pedestrian model for performing calculations even in the design preparation stage. From a historical perspective, impact tests and pedestrian protection were not paid significant attention. There should also be a methodology for data collection and evaluation across the public transit company. The data collected within the Czech Republic is inconsistent and hard to analyze. At the beginning of our research, we addressed the question of which dummy configuration with respect to the tram is most appropriate for our crash tests.**

**Keywords:** Kinematic Analysis, Head, Injury, Tram, Experiment

## 1 Introduction

Various literature indicates a connection between the starting standing posture and the direction of a fall and the severity of the resulting head injury. For example, the work [1] performed measurements with a Hybrid III anthropomorphic test dummy (ATD) for forward, back, and lateral falls. They obtained kinematic data as well as data from force plates and head accelerometers. HIC 15 was used as an injury predictor. For the lateral fall, the mean values of the maximum translational acceleration (206 g for women and 355 g for men) and HIC 15 (598 for women and 2,128 for men) were relatively lower as compared to falls in the forward and back directions. [1]

The biomechanical criterion of injury is an empirically deduced mathematical term that is determined based on the comparison of the physical quantities and severity of the injury caused by the action of such forces. A number of criteria were gradually determined.

The basic biomechanical criteria for injuries to humans, including passenger car drivers, are set based on the biomechanical injury criteria. The most frequently used scale for injury evaluation is AIS – Abbreviated Injury Scale [2]. AIS expresses the severity of injury on a scale from 0 to 6, and unknown cases are classified at 9. Bullets below contains the injury severity by individual body region according to AIS [2].

AIS points:

- 0 – no injury
- 1 – minor injury
- 2 – moderate injury
- 3 – serious injury – not life-threatening
- 4 – severe injury – life-threatening, survival probable
- 5 – critical injury – survival uncertain
- 6 – maximal injury – impossible to survive, fatal injuries
- 9 – unknown injury

The head is the most critical part of the human body in terms of the injury severity and frequency. The declared average weight of the head for 50% of the male population is 4.54 kg, and the average moments of inertia are $I_{xx}$ = 0.0220 kg·m², $I_{yy}$ = 0.0242 kg·m², and $I_{zz}$ = 0.0159 kg·m².

HIC – Head Injury Criterion – is the criterion most frequently applied for the assessment of a head injury in vehicle crash tests. In the period of a high number of destruction tests of passenger cars, it was the input for calculating the course of acceleration on the dummy's head. The criterion value was determined from the given time interval of the total acceleration. The time interval of 36 ms, resp. 15 ms, is determined from the area of the course of the maximum acceleration values. This is the maximum area under the curve created by the superposition of all three axes of acceleration over time. The final value HIC36 is used if the head did not come in contact with the fixed part of the vehicle, and the time interval HIC15 is used if there is contact with the head.

The final value of HIC or its alternative HPC (Head Performance Criterion) should not exceed 1 000, which is considered the limit for a personal injury with the following criteria [3,4]:

- 18% probability of a serious head injury for an average adult;
- 55% probability of a severe head injury for an average adult;
- 90% probability of a moderate head injury for an average adult.

The National Transportation Biomechanics Research Center (NTBRC), however, recommends adjusting this interval for calculation to *t* = 15 ms and adjusting the existing limit value of HIC to 700. An injury to the cervical spine often correlates with the head load. The research as such and cervical spine models are the subject of relatively recent research.

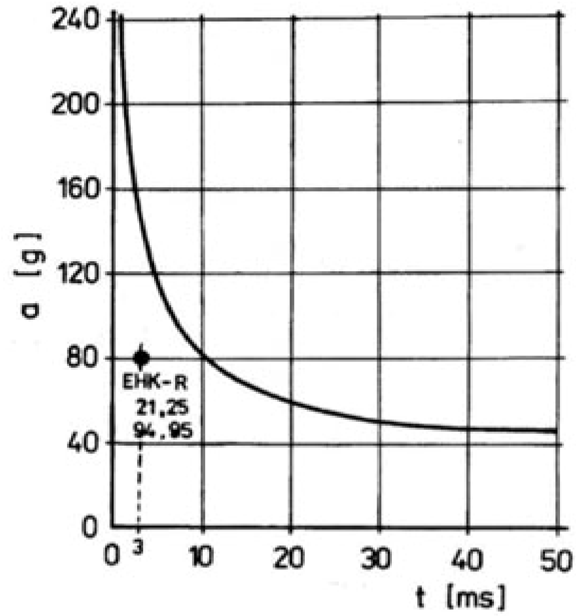


***Fig. 1*** *The WSU Curve*

The head (human brain) load limits are determined by the WSU (Wayne State University) curve that indicates the translational deceleration of the head *a* [m.s$^{2}$] depending on the time of action *t* [s]. The WSU curve is shown in Fig. 1. The curve divides the area into two parts. The values situated above the WSU curve are assessed as life-threatening. The values situated under the curve are assessed as tolerable values. This curve is determined only for a frontal crash onto a flat surface, but it was used to determine the limit of 80 g for a duration of 3 ms [5].

Further, the Severity Index (SI) is used and was determined based on the WSU curve. It determines the value of SI = 1 000 as the survival limit. The actual SI value is calculated using the following formula:

$$\boldsymbol{SI = \int_0^t {a_r}^{2,5}\, dt,} \tag{1}$$

Where:

*t*…The end of impact [s],

$a_r$...The final value of deceleration in the directions of axes x, y, and z [m.s$^{-2}$].

Neck Injury Criterion (NIC). As a cervical spine injury is caused by the moment induced by the head inertial force, NIC monitors the correlation between the injury and liquid flow (gradient) inside the cervical spine. The limit value for this NIC criterion is fixed at 15 m$^{2}$.s$^{-2}$. The moment of neck flexion around axis y must be below 57 Nm [6].

$$\boldsymbol{NIC = a_r \cdot 0,2 + {v_r}^2,} \tag{2}$$

Where:

$a_r$...The head acceleration [m.s$^{-2}$],

$v_r$...The velocity of the head center of gravity [m.s$^{-1}$].

There are also the recommended values for the maximum moment of flexion determined for cervical spine injuries:

- Front flexion - 50.2 Nm
- Back flexion - 20.3 Nm
- Lateral flexion - 47.5 Nm

Another possible criterion is 3 MS (three-millisecond criterion). This criterion states that the cumulative acceleration exceeding 60 g, measured at the test, shall not last for more than 3 ms. This is the simplest criterion based on the measurement of a single quantity and is applicable to a number of biological tissues, organs, and sub-systems.

This section contains the commonly-used criteria for determining an injury to the head or cervical vertebrae. There are a number of other criteria, such as NIJ (Normalized Neck Injury Criterion), ThPC (Thorax Performance Criterion), TTI (Thoracic Trauma Index), CTI (Combined Thoracic Index), ThCC (Thoracic Compression Criterion), and others which, however, mostly deal with other parts of the body and mainly serve as the criteria for vehicle crash tests [7–8].

There is a new issue of using noise-cancelling headphones. Based on information from the Police of the Czech Republic, there were 76 fatal accidents and 245 severe injuries related to a tram collision with a pedestrian in the period from 1 January 2007 to 1 July 2020 [9].

Our project dealt with the analysis of statistical information about accidents. Based on all identified data, the best configuration for the crash test with a dummy was selected for obtaining real-time responses. This output will be used to validate the finite element model of a pedestrian for a specific model situation so that it can further be used for the verification of values in the development of new tram types.

A pre-experiment was conducted in the second phase in order to test the reality of performing the selected configuration and selected speeds, as well as to test the measuring equipment and validity of output values. This paper, therefore, deals with this pre-experiment, the observations of which will be used to compile a set of final crash tests and to determine the range of biomechanical criteria.

The severity of injury is assessed most often using the Head Injury Criterion (HIC), defined as follows:

$$\boldsymbol{HIC} = \left\{(\boldsymbol{t_2} - \boldsymbol{t_1})\left(\frac{\boldsymbol{1}}{\boldsymbol{t_2} - \boldsymbol{t_1}}\int_{\boldsymbol{t_1}}^{\boldsymbol{t_2}} \boldsymbol{a(t)dt}\right)^{\boldsymbol{2{,}5}}\right\}_{\boldsymbol{max}}, \tag{3}$$

Where:

$a(t)$ …The final value of head acceleration,

$t_1$, $t_2$...The variables for the start and end time intervals during which HIC achieves the maximum value.

For controlling purposes, the maximum of interval $t_1$ and $t_2$ is fixed at 15, resp. 36 ms. The time interval used is then stated as the lower index by the abbreviation, e.g. HIC36. The head injury criterion (HIC) is used based on the proposal of the National Highway Traffic Safety Administration (NHTSA) of 1972 [10].

The issue of human load in the field of road transport is currently a highly addressed topic [14-18].

## 2 Methods

The first set of crash tests was performed as the lateral hitting of a pedestrian by a KT8D5-type tram. This is a tram used by Dopravní podnik hlavního města Prahy (Prague Public Transport Company) and was manufactured by ČKD Praha, Tatra Smíchov Facility. It was manufactured in the period of 1986–1993 in the quantity of 199 units. The tram without the couplers is 30,300 mm long, 2,480 mm wide, and 3,145 mm high. The curb weight is 38,000 kg and the maximum speed is 65 km.h$^{-1}$.

The crash tests were conducted at the speed of 10 and 20 km.h$^{-1}$. It consisted of a direct lateral crash into the left third of the tram front end at the speed of 10 and km.h$^{-1}$ (see Fig. 2). Further, a lateral crash at the edge of the tram front end and side was conducted at the speed of 20 km.h$^{-1}$ (see Fig. 3). The crash test was conducted under laboratory conditions in the test department of the Dopravní podnik hlavního města Prahy depot.

We used a dummy of a typical representative of the male population (Jasti Hybrid III, 50th Percentile Male with Pedestrian kit), Hybrid III.

Both the dummy and the tram front end were fitted with a set of reflective points of the Qualisys system for scanning 3D kinematic data. A set of 8 cameras with the recording frequency of 300 Hz was used. The entire scene was scanned by two high-speed cameras from the side and oblique views.

## 3 Results

The experiment can be evaluated by analyzing the data from the Qualisys system as well as by analyzing the high-speed camera recordings.

A detailed analysis of the high-speed camera recordings confirms some of the known patterns. In the starting crash action, the body forms a shape according to the crash edge shape at the speed of 10 and 20 km.h$^{-1}$. The first contact occurs in the thigh and hip region. The body achieves the tram's speed by means of a huge acceleration. Due to the high strength of the tram crash edge material, the entire energy is absorbed by the body. Subsequently, the head impacts the transition of the body and windshield. For the purposes of further analysis, we will consider the head impact a secondary impact. The body is subsequently thrown forward, resp. it continues the forward movement, unlike the tram which had activated intensive braking. The tertiary impact follows, i.e. the impact of the body onto the ground. Upon impact at the edge of the tram front end and side, the body is thrown away crossways after the secondary head contact.

***Fig. 2*** *Direct lateral crash with the left third of the tram front end*


***Fig. 3*** *Lateral crash with the edge of the tram front end and side*

An analysis of the Qualisys system data enabled a reconstruction of the precise trajectory and speed of movement of the body and the impact edge (see Fig. 4). It is obvious that after the initial dragging of the body by the tram, the body predictably continues moving forward, i.e. it is not thrown upwards. On the contrary, there is an obvious effect of friction between the skin and shoes. The course of speed is shown in Fig. 5, 6. Here, we shall mention the failure of the speed recording when it ends at time 0.5s for the speed of 20 km.h$^{-1}$. This was caused by the improper setting of the time parameters for recording. For the purposes of interpreting the results, we shall mention that while the head and trunk speed sharply increased to the maximum value right after the primary contact at the speed of 20 km.h$^{-1}$, the head speed records for the speed of 10 km.h$^{-1}$ indicate a moderate increase of the speed after the secondary impact and then a rapid decrease thereof.

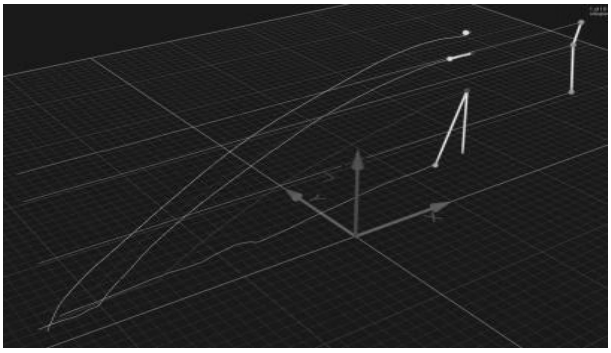

***Fig. 4*** *Reconstruction of the body movement and tram impact edge*

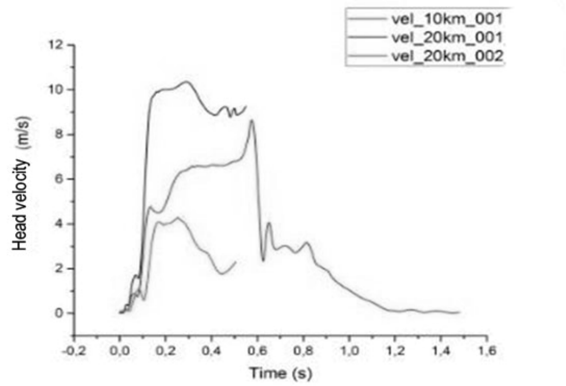


***Fig. 5*** *Illustration of the time path of speed in the region of the head*

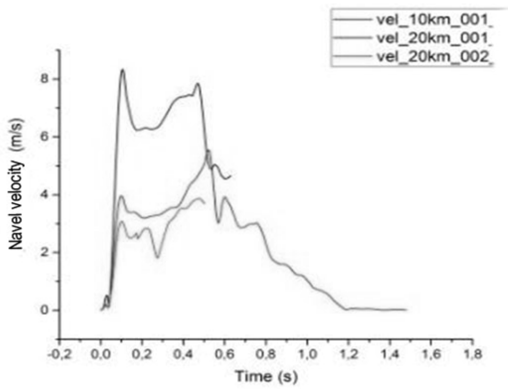


***Fig. 6*** *Illustration of the time path of speed in the region of the navel*

The maximum trunk speed was 5.4 m.s$^{-1}$ for 10 km.h$^{-1}$, 8.2 m.s$^{-1}$ for 20 km.h$^{-1}$ frontal crash, and 3.9 m.s$^{-1}$ at 20 km.h$^{-1}$ lateral crash. The head achieved the maximum speed of 8.3 m.s$^{-1}$ at the tram speed of km.h$^{-1}$, 10.2 m.s$^{-1}$ at the speed of 20 km.h$^{-1}$ and lateral crash, and 4.3 m.s$^{-1}$ at the speed of 20 km.h$^{-1}$ and lateral crash. Therefore, there is a highly apparent acceleration of the head movement at the tram speed of 10 km.h$^{-1}$ caused by the rotary movement of the body – in the front-to-back plane, perpendicular to the tracks.

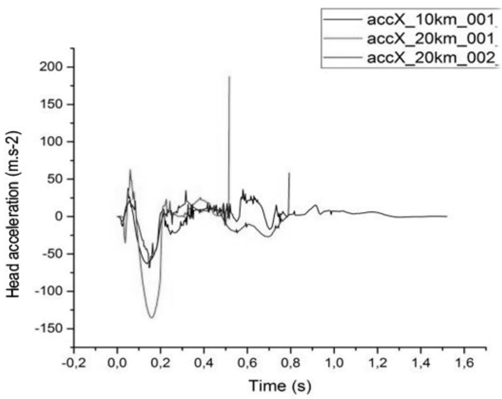


***Fig. 7*** *Illustration of the time paths of acceleration in the region of the head*

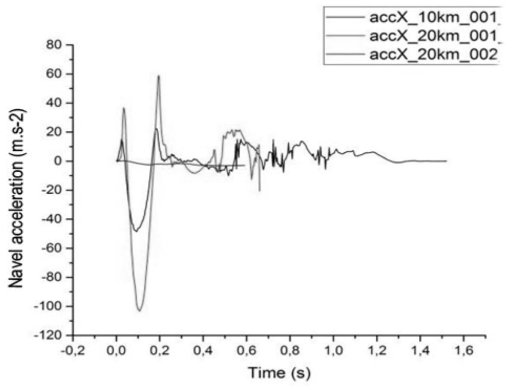


***Fig. 8*** *Illustration of the time paths of acceleration in the region of the navel*

Based on the head acceleration value (see Fig. 7, 8) we can conclude that the first acceleration peak occurs in course of the primary crash, which affects the mechanism of the injuries sustained. The acceleration increases with increasing speed. A major acceleration peak follows during the secondary crash. At the tram speed of 20 km.h$^{-1}$, there is a very significant acceleration peak apparent during the tertiary crash, i.e. upon contact with the ground, when this acceleration of the head is at the maximum value and, in terms of the injury severity, this value is the most significant for the determination thereof.

## 4 Discussion

In terms of the injury criteria, we analyzed the frontal crash for both speeds (see Fig. 9 and 10).

At the speed of 10 km.h$^{-1}$, the maximum acceleration of 61 g was measured, the 3 ms injury criterion achieved the value of 59 g, and the HIC value was 386. With the correlation of the HIC value with the AIS table, we can conclude an eventual injury at the minor injury level.

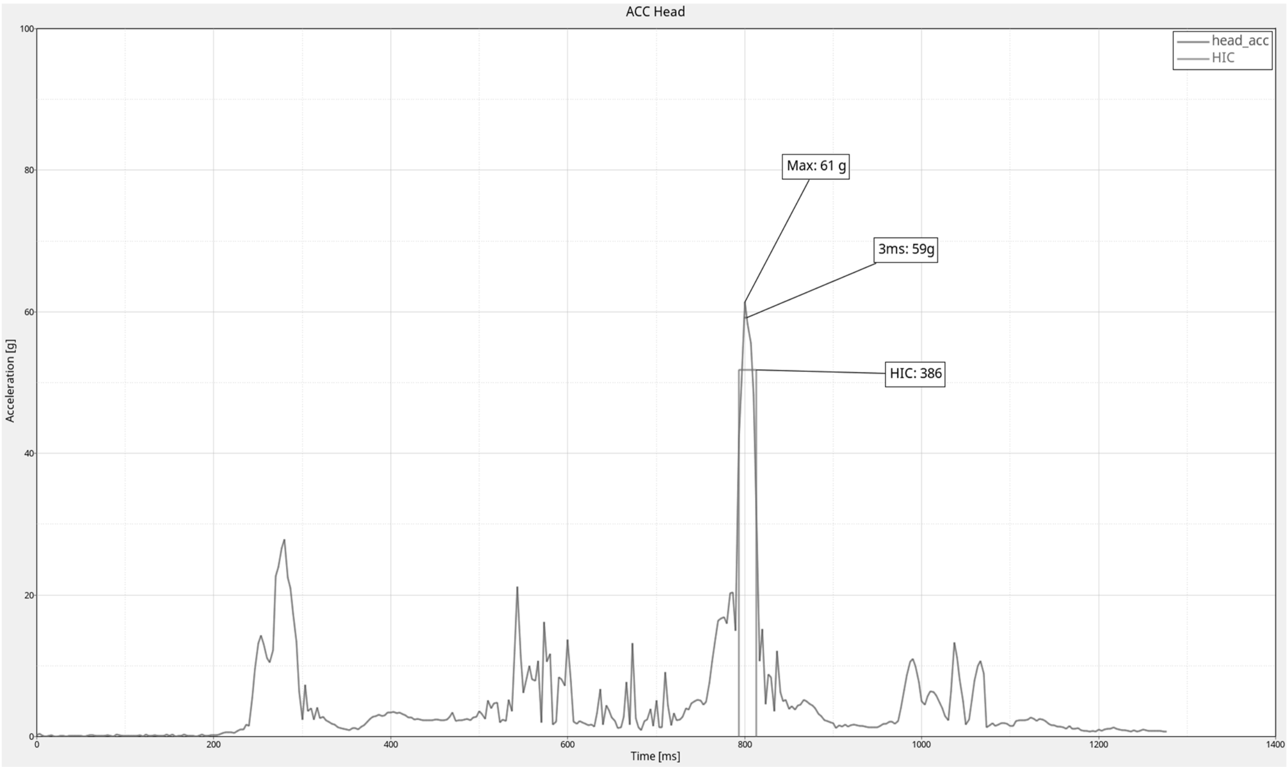


***Fig. 9*** *Biomechanical head injury criteria for the speed of 20 km/h*

At the speed of 20 km.h$^{-1}$, the maximum acceleration of 86 g was measured, the 3 ms injury criterion achieved the value of 78 g, and the HIC value was 754. With the correlation of the HIC value with the AIS table, we can conclude an eventual injury at the moderate injury level. However, the limit value of HIC 1 000 was not achieved.

With respect to the purpose of the experiment, i.e. to test the methodology of performing the crash test and verify the functionality of the sensors, a simple injury analysis was carried out using HIC. Further measurement will be performed using a three-axis accelerometer, and the rotary acceleration will be analyzed as well. For the consequences of the direct impact, it has, however, been proven that HIC is an acceptable discriminator between a serious and moderate injury [11]. It also correlates with the risk of skull fracture [13]. For impacts from various directions, improper correlation between HIC and the injury severity was identified, as the head rotation, which is often the primary cause of various types of traumatic brain injuries, was not taken into account [10]. The head injury criterion including the head rotation was proposed as well, but it was never properly evaluated [12]. HIC predicts the risk of injury from an external mechanical head impact that can be measured directly from the crash test dummy, but it does not take into account the internal mechanical response. Besides, the individual types of traumatic brain injuries are not distinguished [10-12].

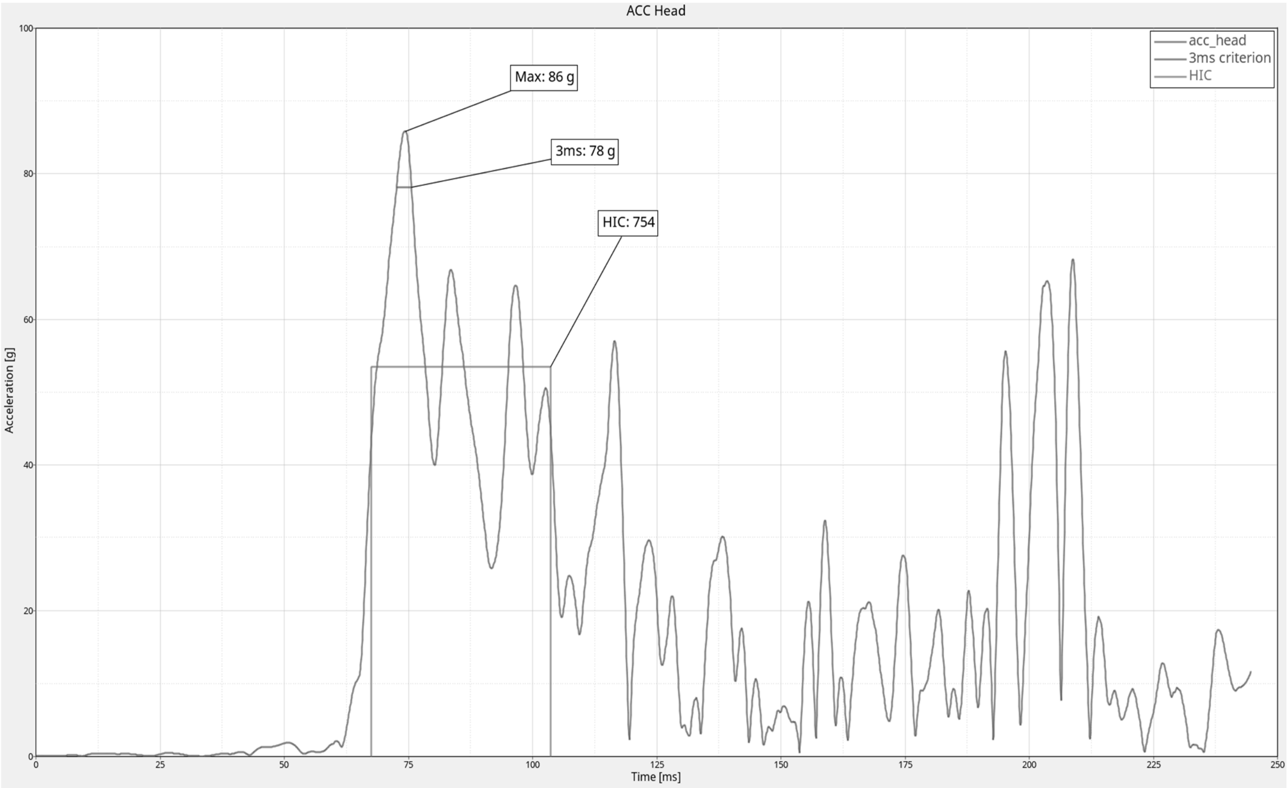


***Fig. 10** Biomechanical head injury criteria for the speed of 20 km/h*

The performance of the crash test can be considered a success. The data used for conducting the kinematic analysis was scanned and can be used for the dummy validation. The speed data indicated the above-mentioned failure caused by a short measurement. The results of the biomechanical head injury criteria indicate realistic values, and we can conclude that the pre-experiment did not reveal a major defect for performing the final set of crash tests with a sufficient amount of data so that the required conclusions can be validated statistically.

## Acknowledgement

***The article was created with the contribution of the grant OP VVV CZ.02.1.01/0.0/0.0/16_026/0008401 UK Praha.***

## References

[1] HAJIAGHAMEMAR, M., SEIDI, M., FERGUSON, J. R., & CACCESE, V. (2015). *Measurement of head impact due to standing fall in adults using anthropomorphic test dummies*. Annals of biomedical engineering, 43(9), 2143-2152

[2] KREJČÍ, J. (2012). *Pasivní bezpečnost dvoustopých vozidel z hlediska biomechaniky poranění posádky*, ČZU v Praze

[3] KOVANDA, J. a kol. (2016). *Bezpečnostní aspekty návrhu dopravních prostředků*. ČVUT v Praze, ISBN 978-80-01-05893-0

[4] HOŠEK R. (2012). *Systémy pro sledování únavy řidiče*, VUT v Brně

[5] KOVANDA, J., ŠATOCHIN, V. (2000). *Pasivní bezpečnost vozidel - 1. vydání*, Vydavatelství ČVUT, Praha, ISBN 80-01-02235-8

[6] ŠPIRK S. (2015). *Metodické problémy výzkumu pasivní bezpečnosti a deformační odolnosti konstrukcí kolejových vozidel*, Plzeň

[7] KRAHULÍK, D. (2006). *Kraniocerebrální poranění*, NCH klinika Fakultní nemocnice Olomouc

[8] HOŠEK R. (2012). *Systémy pro sledování únavy řidiče*, VUT v Brně

[9] *Statistické vyhodnocení nehod v mapě*, Policie ČR. Webová stránka In:

http://maps.jdvm.cz/cdv2/apps/nehodyvmape/Search.aspx; informace získané k 30.07.2020

[10] MARJOUX, D., BAUMGARTNER, D., DECK, C., WILLINGER, R. (2008). H*ead injury prediction capability of the hic, hip, simon and ulp criteria.* Accid Anal Prev 40 (3), 1135-48

[11] TARRIERE, C. (1981). *Head and neck injury criteria - a concensus workshop.* NHTSA, Washington D.C. : U.S., pp. 218-228

[12] BRANDS, D.W.A. (2002). *Predicting brain mechanics during closed head impact*: Numerical and constitutive. Technische Universiteit Eindhoven, Eindhoven

[13] RAN, A., KOCH, M., MELLANDER, H. (1984). *Fitting injury versus exposure data into a risk function.* In: Proceedings of the International IRCOBI Conference on the Biomechanics of Impact held at Delft, The Netherlands

[14] JEŽDÍK, R., KONOPNÍK, P., RUND, M., SVOBODA, M, JELEN, K. (2021). Determination of material properties of laminates of 15T and T3 tram faces. In: *Manufacturing Technology*, Vol. 21, No. 4. pp. 912-916, ISSN: 1213-2489 DOI: 10.21062/mft.2021.040

[15] ČERNOHLÁVEK, V., SVOBODA, M., ŠTĚRBA, J., CHALUPA, M., SAPIETA, M. (2020). Analytical and experimental solution of vibrations of a system of bound bodies, In: *Manufacturing Technology*, Vol. 20, No. 6 , pp. 699-707, ISSN: 1213-2489, DOI: 10.21062/mft.2020.116

[16] SVOBODA, M., VAN DER KAMP, K., JELEN, K. SAPIETA, M. (2019). Identification of changes in mechanical properties of human axial system due to stress and relaxation regime, In: *Manufacturing Technology*, Vol. 19, No. 5, pp. 860-867, ISSN: 1213-2489

[17] LOPOT, F., KUBOVY, P., JELEN, K., ŠORFOVÁ, M.,, TLAPÁKOVÁ, E., RULC, V., PURŠ, H., JEŽDÍK, R., SVOBODA, M. (2019) *Kolize chodce s tramvají – pilotní experiment.* CD – ROM pp. 116-121, VI. mezinárodní konference „Experimentální a výpočtové metody v inženýrství 2019“, Ústí nad Labem, ISBN 978-80-7561-185-7

[18] SVOBODA, M., SOUKUP, J., JELEN, K., KUBOVÝ, P. (2015). Effect of Impact on Human Head, In: *Manufacturing Technology*, Vol. 15, No. 2, pp. 226-231, ISSN: 1213-2489