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The Biomechanics of Head Injuries during Tram-Pedestrian Accidents

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The goal of the study was to analyse the kinematic and dynamic response of the human head during the primary impact of tram-pedestrian collisions. The anthropomorphic test device (dummy) was used for two collision scenarios: the frontal (dummy facing the approaching tram) and side impact (dummy standing with its shoulder towards the tram). The crash tests were conducted with four different types of tram, typical for the Prague's public transportation, and at four different impact speeds (5, 10, 15, 20 km/h). The primary outcome variable was the resultant head acceleration. The risk and severity of possible head injuries were analysed using the head injury criterion (HIC_{15}) and the corresponding level of injury on the Abbreviated Injury Scale (AIS). The results of kinematic analysis showed that during the primary impact, the head of dummy always got hit by trams' front ends in the case of frontal impact while in the case of side impact, the head got only hit at higher speeds (15 and 20 km/h) with modern tram types. The results of dynamic analysis showed an increasing trend of head impacts with higher speeds for all tram types and collision scenarios. However, the head acceleration was higher in the case of frontal impacts compared to side impacts. The HIC_{15} did not exceed the value of 300 in any case and the probability of AIS3+ did not exceed 10%. The results suggest that the outcomes of tram-pedestrian collisions can be influenced by the tram type (its front-end design), impact speed, collision scenario, and the site of initial contact.

Keywords: Collision; tram; dummy; head impact; crash test.

1 Introduction

In recent years, there has been a lot of emphasis placed on public transportation in order to improve the environmental and climatic conditions – air quality in cities, emissions reduction, traffic and its noise. As the traffic density has grown greater over the past decade, the incidence of tram collisions with pedestrians, cyclists and motor vehicles has increased. In addition, pedestrians' lack of attention due to "smart" plays another important role [1,2].

According to a study by Horberry (2019), approximately 273 people are killed on the roads worldwide each year. For this reason, pedestrian safety on roads has currrently become a global concern [3,4]. Road traffic-related accidents are one of the most common causes of the injuries [5,6].

Based on the data from several studies focused on the biomechanical response of human head to the impact, a head impact tolerance curve, known as the Wayne State Tolerance Curve (WSTC, Fig. 1), has been defined. The curve describes the relationship between head acceleration (a (g)), duration of the acceleration (t (ms)), and the onset of concussion. Any impact above this curve can be life-threatening. The curve shows that the head can withstand very high accelerations but for very short time [7-10].

The WSTC was used to develop and define currently used injury assessment criteria, such as the Head Injury Criterion (*HIC*) [11,12]. Its European equivalent is the Head Protection Criterion (*HPC*) [10,13,14]. The head injury criterion is defined as:

$$HIC(\Delta t_{max}) = max\left[\left(\frac{1}{t_2 - t_1}\int_{t1}^{t2} \hat{a}\, dt\right)^{2.5} \cdot (t_2 - t_1)\right] \quad (1)$$

Where:

t_1 and t_2…The initial and final time of the acceleration pulse,

$\hat{a}$…The normalised head acceleration, i.e., the ratio of the measured and gravitational acceleration.

The National Highway Traffic Safety Administration (NHTSA) adopted the limits that reduced the maximum time interval for estimating *HIC* to 15 ms (HIC_{15}) as relatively short-duration impact waveforms are considered to be associated with a head contact [15,16].

In the 1960s, an injury scale called the Abbreviated Injury Scale (AIS) was developed to clasif and describe the severity of traumatic injuries [17]. The severity of these injuries is rated numerically from 1–6, one being a minor injury and six indicating a currently untreatable injury.

Based on the calculated values of the head injury criterion, the probability of head injury risk (p (%)) on the AIS scale, can be determined using correlation equations, based on the cadaver experiments by Prasad and Mertz, and illustrated in a sigmoid form (Fig. 2) [4,18,19]. According to Prasad and Mertz (1985), a value of HIC_{15} = 700 represents less than a 5% risk of a life-threatening brain injury [20]. Values above this limit carry a high risk of severe head injuries [11,21].

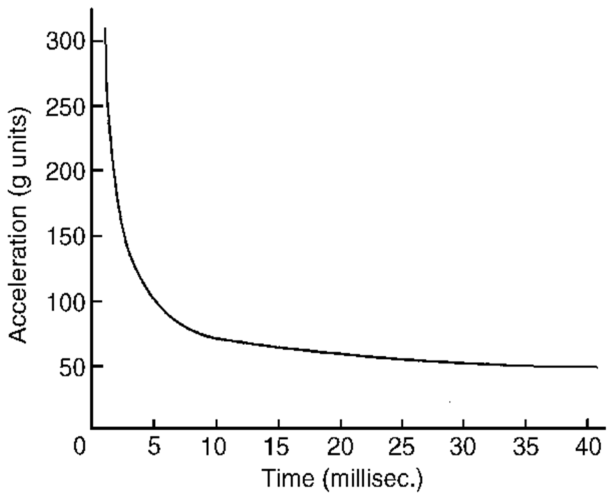

Fig. 1 *WSTC head impact resistance curve [9]*

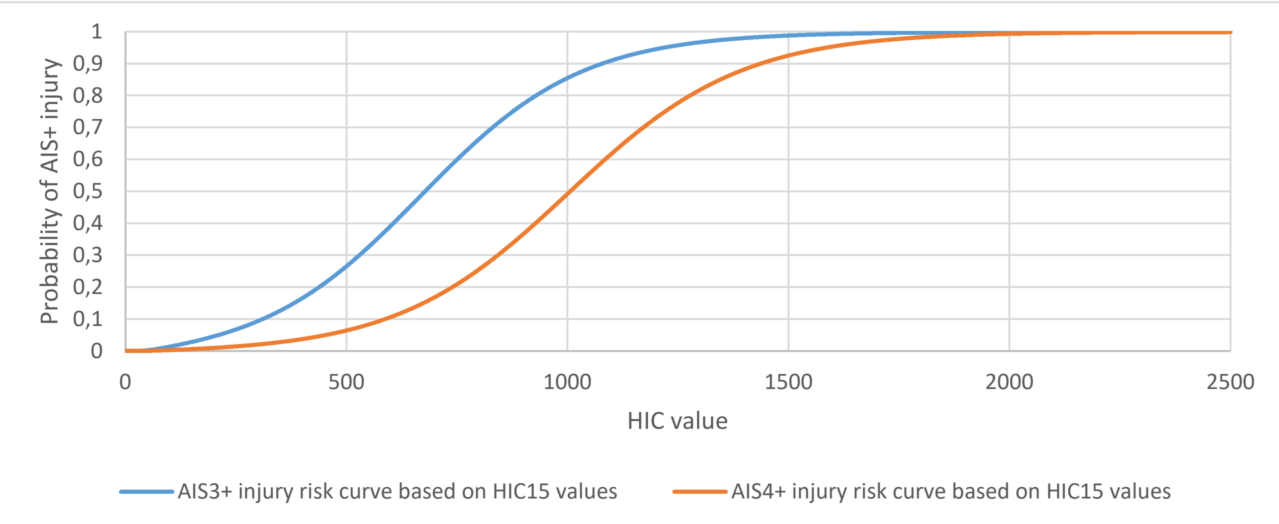

Fig. 2 *Head injury risk curves based on HIC15 values for AIS3+ and AIS4+ injuries*

The purpose of this study was to analyse the biomechanical load on the dummy‘s head during the primary impact of crash tests with a tram front end. A standardised Hybrid III 50th Percentile Male Pedestrian Dummy (JASTI, Tokyo, Japan) was used for the tests. The analysis was focused on the severity of head injuries at four different speeds (5 km/h, 10 km/h, 15 km/h and 20 km/h), four types of tram front ends and two dummy positions – frontal and sagittal.

2 Methods

Four tram types, typical for the Prague's public transportation, were used for the purposes of crash tests. The trams differed from each other based on the manufacture year and the front-end design (Fig. 3). The oldest model, T3R.PLF produced by Tatra from the 1960s to 1990s (Fig. 3 – top left), is characterized by a high body chassis, a bent-shaped windscreen, and two front-mounted bulbous headlamps. Another older type of tram, KT8D5 produced by Tatra from the 1980s to 1990s (Fig. 3 – top right), is characterized by a lower body chassis, and bigger and bent-shaped windscreen. It is described by Fanta (2022) in more detail. Two modern tram types (14T, Fig. 3 – bottom left; 15T, Fig. 3 – bottom right) were designed and manufactured by Skoda Transportation and they are characterized by low-deck design, and bigger windscreen, especially in the case of 15T. Most importantly, they follow the technical report by The European Committee for Standardization (CEN/TR 17420) regarding the tram's front-end design with respect to pedestrian safety. A total of 32 crash tests were conducted using a 200m straight tramway track at the testing facilities of the VÚKV a.s. Trams travelled at four different impact speeds (5, 10, 15, 20 km/h). There were 32 crash tests conducted in total, one for each tram type, speed, and collision scenario (frontal or side impact). Therefore, any detailed statistical analysis could not be done and it is one of the main limitations of the study.

Fig. 3 *The tram types used for the crash tests (top left – T3R.PLF; top right – KT8D5; bottom left – 14T; bottom right – 15T)*

The biomechanical response of a pedestrian during the crash test wih a tram was analysed using the Hybrid III 50^{th} Percentile Male Pedestrian Dummy. The dummy was equipped with several wireless accelerometers, gyroscopes, and dynamometers (Fig. 4) with recording frequency of 20000 Hz. The kinematics of dummy was recorded by two high-speed cameras (Photron, Tokyo, Japan), one being placed in the area of primary impact, the recording frequency of 12000 Hz, and one recording the whole collision scenario from a distance (the recording frequency of 500 Hz). The dummy was also equipped with external sensors (reflective passive markers) recorded by the Qualisys motion capture system (Qualisys AB, Göteborg, Sweden), at the frequency of 300 Hz, to analyse the kinematice of dummy's body parts.

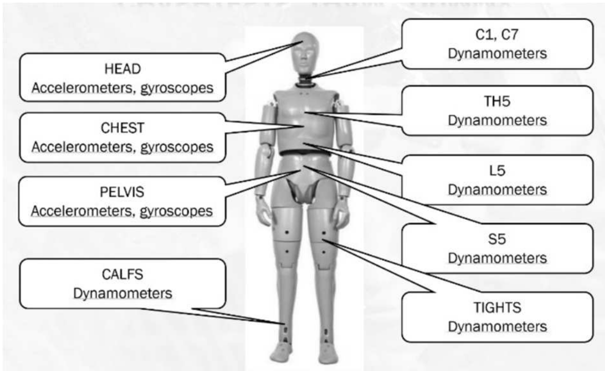

Fig. 4 *Internal body sensors used to record the kinematics and dynamics of a dummy during a collision*

The dummy's position on a track followed the recommendations developed by the CEN in the current technical report (CEN/TR 17420). The dummy was, therefore, placed at a distance equal to the 15% value of half of the tram width from the centre line towards one end of the track. Although the report only considers the case of side impact collision, this study also included the frontal impact due to the dummy being validated only for frontal crash tests. This represents another limitation of the current study and future direction [22].

The primary outcome variable was the resultant head acceleration during the primary impact and the head injury criterion (HIC_{15}) to assess the risk and severity of a given head injury. The values of head injury criterion were then linked to an injury level on the Abbreviated Injury Scale (AIS), where the AIS1 represents minor injuries and AIS6 represents a virtually unsurvivable injury. The studies mostly focused on the determination of AIS3+ (i.e., AIS $\geq$ 3) or AIS4+ (i.e., AIS $\geq$ 4) injuries, which correspond to HIC_{15} values higher than 900. Such injuries are considered to be serious/severe or worse.

3 Results

A total of 32 crash tests were conducted for each tram type, impact speed, and collision scenario (frontal and side impact). The kinematic data were collected using two technologies; the Qualisys motion capture system was used to analyse the motion of dummy's body parts and front end of trams and high-speed cameras were used to record the whole kinematics of the collision. The dynamic data were collected using dummy's in-body sensors and for the purpose of this study, the resultant head acceleration during the primary impact was assessed. The primary impact was defined by the initial contact of tram hitting the dummy and it ended when there was no obvious contact between both bodies (the dummy was pushed forward by a tram that started to brake). There was one failed measurement for the KT8D5 tram type at the speed of 20 km/h for both collision scenarios.

An example of movement analysis for the T3R.PLF tram type at the speed of 5 km/h for the side impact can be seen in Figure 5 (Fig. 5). Firstly, the tram hit the dummy in the hip area (the initial contact, Fig. 5 – left). The dummy's upper body then started to tilt towards the tram, which hit the dummy's shoulder (Fig. 5 – middle). Finally, the dummy's body was lifted off the ground, its head tilted even more towards the tram, without a direct impact, and it continued the forward movement while the tram started to brake (Fig. 5 – right). The results of movement analysis for other tram types, impact speeds, collision scenarios are shown in Table 1.

Fig. 5 *The movement/video analysis of the primary impact in the case of side impact for the T3R.PLF tram type at the speed of 5 km/h*

Tab. 1 *The results of video analysis of primary impact regarding the area of initial contact and a direct head impact*

FRONTAL IMPACT				SIDE IMPACT	
Contact with the head	The area of initial contact	Speed (km/h)	Tram type	Contact with the head	The area of initial contact
YES	Head/Pelvis	5	T3R.PLF	NO	Arm/Hip
YES	Hip/Lower extremity	10		NO	Arm/Hip
YES	Hip/Lower extremity	15		NO	Arm/Hip
YES	Hip/Lower extremity	20		NO	Pelvic region
YES	Thoracic region	5	KT8D5	NO	Upper extremity region
YES	Head	10		NO	Thoracic region
YES	Head/Thoracic region	15		NO	Arm/Hip
YES	Abdomen/Pelvis	5	14T	NO	Pelvic region
YES	Abdomen/Chest	10		NO	Hip/lower extremity/knee
YES	Abdomen/Pelvis	15		NO	Pelvic region
YES	Abdomen/Pelvis	20		YES	Pelvic region/Hip/Knee
YES	Pelvis/Hip	5	15T	NO	Hip-lower extremity/Knee
YES	Pelvis	10		NO	Pelvis
YES	Pelvis/Hip	15		YES	Pelvis/Knee/Lower extremity
YES	Pelvis	20		YES	Pelvis

The results showed that the dummy's head was hit by all tram types at each impact speed during the frontal primary impact. In three cases, the head was hit during the inital contact (highlighted in yellow), otherwise the head was always hit as a part of following contacts with a tram. On the other hand, during side impact, the contact with the head only occurred in three cases (highlighted in grey), at higher impact speeds and only with modern tram types (14T at 15 km/h and 15T at 15 and 20 km/h). The head was not a part of initial contact in any of these cases. The hip/pelvic region and thoracic region were the most frequent areas of initial contact for both collision scenarios.

Regarding the resultant head acceleration and its progress over time during the frontal primary impact, the results showed increasing values with higher impact speeds for all tram types (Fig. 6). The duration of impact was quite short (reaching maximally 40 ms) and the maximum values of head acceleration were similar for all tram types except higher values for the 15T tram type. However, the the maximum values did not exceed 125 g.

Regarding the resultant head acceleration and its progress over time during the side primary impact, the results showed similar trend to the frontal impact, i.e., higher values with increasing impact speed (Fig. 7). However, except the 15T tram type, the duration of impact was much longer (up to 100 ms), the shape was not as sharp as in the case of frontal impact, and the values of head acceleration were smaller (up to 30 g). In the case of 15T tram type the maximum values of acceleration were higher, reaching up to 85 g, and the duration was similar to the frontal impact.

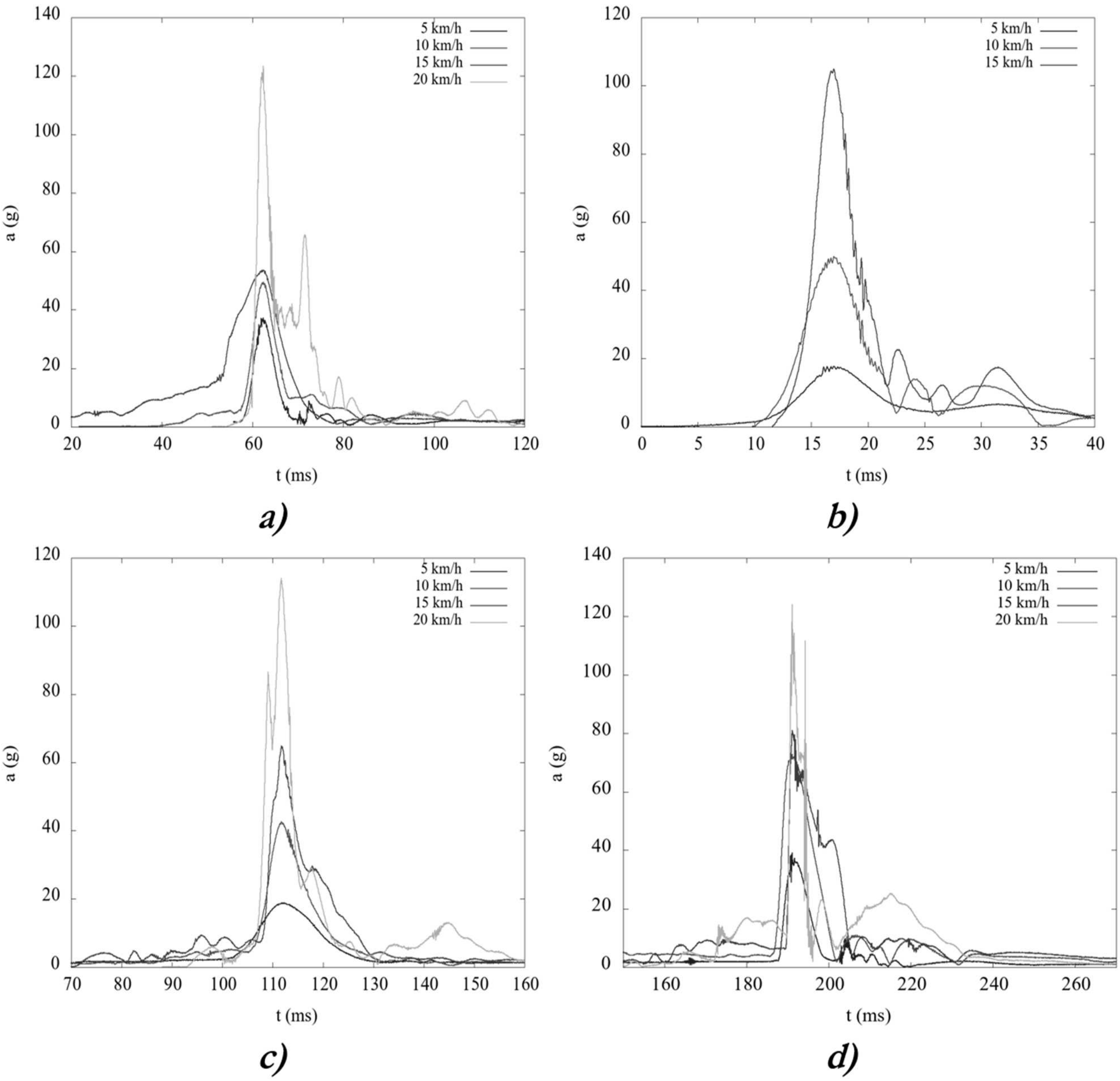

Fig. 6 *The progress of resultant head acceleration over time during the frontal primary impact (a) T3, b) KT8, c) 14T and d) 15T)*

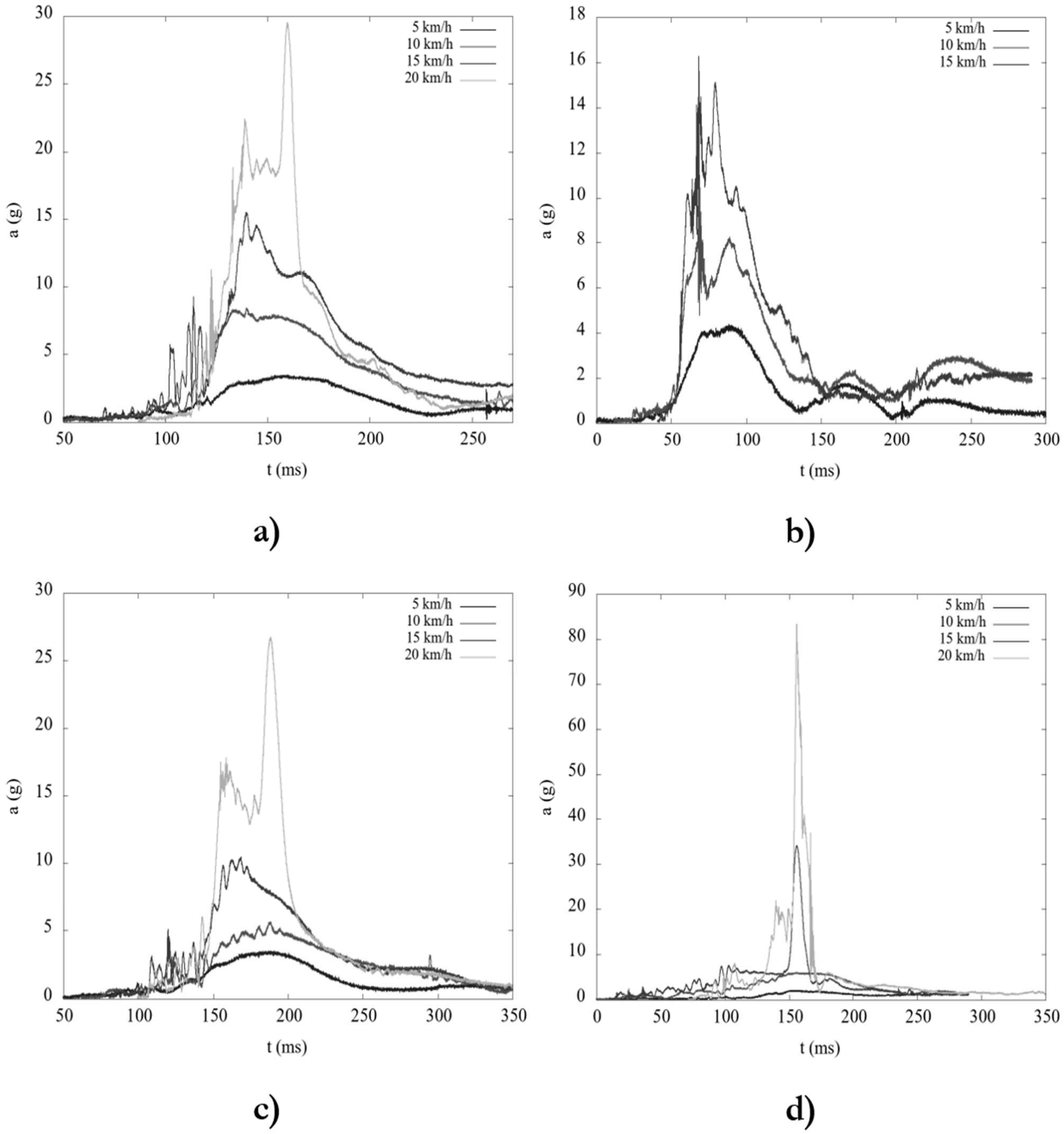

Fig. 7 *The progress of resultant head acceleration over time during the side primary impact (a) T3, b) KT8, c) 14T and d) 15T)*

In the case of both collision scenarios, the corresponding HIC_{15} showed similar trends with higher speed to the resultant head acceleration (Fig. 8, Tab. 2). Except the 15T tram type, the results for each tram type did not differ significantly. The values were considerably lower for the case of side impact (HIC_{15} did not exceed the value of 35) compared to the frontal impact, but the values were not higher than 300. Therefore, the probability of AIS3+ and AIS4+ injuries fell within the range of 10 % for all tram types, impact speeds, and collision scenarios (Tab. 2).

However, the 15T tram type showed significantly higher values for both collision scenarios. In the case of frontal impact, the values rose steadily until the speed of 20 km/h. At that moment, the windscreen got damaged and cracked due to the impact and the value dropped significantly. The kinetic energy was partly dissipated into dislocations, cracks in the glass, and then its material properties changed dramatically ("softened") during the impact. In the case of side impact, the values rose steadily and differed significantly from the other tram types at higher speeds (15 and 20 km/h, Tab. 2)).

Tab. 2 *The HIC_{15} values and the probability of AIS3+ and AIS4+ injuries for both collision scenarios*

FRONTAL IMPACT					SIDE IMPACT		
HIC_{15}	AIS3+ (%)	AIS4+ (%)	speed (km/h)	Tram type	*HIC_{15}*	AIS3+ (%)	AIS4+ (%)
11.77	0.00	0.00	5	T3	0.30	0.00	0.00
4.32	0.00	0.00		KT8	0.52	0.00	0.00
11.79	0.00	0.00		14T	0.31	0.00	0.00
16.21	0.00	0.00		15T	0.07	0.00	0.00
38.41	0.11	0.02	10	T3	2.68	0.00	0.00
35.91	0.08	0.02		KT8	2.33	0.00	0.00
45.10	0.19	0.04		14T	0.86	0.00	0.00
159.98	3.18	0.69		15T	1.21	0.00	0.00
139.56	2.53	0.55	15	T3	10.59	0.00	0.00
111.38	1.70	0.37		KT8	8.77	0.00	0.00
107.52	1.60	0.35		14T	4.42	0.00	0.00
239.67	6.29	1.36		15T	29.45	0.03	0.01
281.22	8.36	1.82	20	T3	33.04	0.06	0.01
-	-	-		KT8	-	-	-
213.02	5.14	1.11		14T	30.77	0.04	0.01
101.06	1.42	0.31		15T	199.11	4.58	0.99

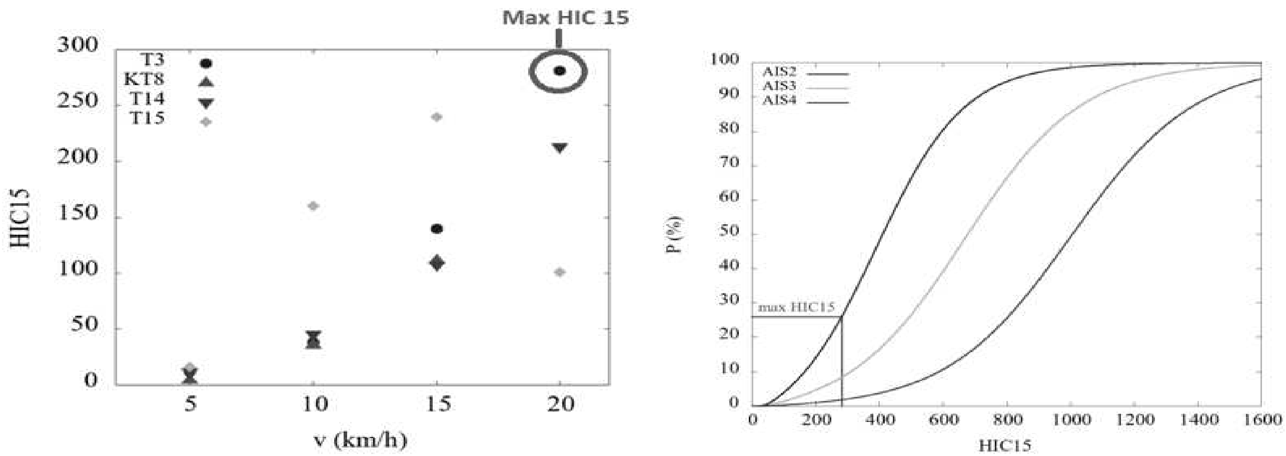

Fig. 8 *The results of HIC_{15} values for the case of frontal impact (left) and the probability of AIS+ injuries (right)*

4 Discussion

All over the world, tram lines and the tram cars themselves are being upgraded in terms of materials used, weight reduction, front body design and much more. The aim of the modifications is to increase the tram safety and reliability for all road users, i.e. not only passengers but also pedestrians. The study focused on the analysis of primary impact resulting from the collision of pedestrian's head and the tram front end using four tram types, typical for the Prague's public transportation, four impact speeds (5, 10, 15, 20 km/h), and two collision scenarios (frontal and side impact). The secondary impact resulting from the pedestrian/dummy being pushed forward by tram and colliding with the surrounding infrastructure (ground, tramway tracks) was not a part of this study.

The analysis focused on tram speeds up to 20km/h, as this is the most common speed close to tram stops. Hedelin (1996) analysed 193 non-fatal and 16 fatal injuries and reported that 147 impacts occurred at or near a tram stop (76 %) [23]. Eleven of the 16 fatalities were connected with accidents at or near a tram stop (69 %). Millot (2016) reported that out of 105 accidents, analysed in four major French cities, almost 70 % occurred in the vicinity of public transport stops [24].

Kovanda (2016) stated that head injuries were one of the most serious injuries in road traffic accidents.

According to statistics, it is a cause of up to 75 % of all deaths in traffic accidents [14]. Hutchison (2007) stated that head injuries were the most critical injuries of the human body in terms of incidence and severity [25]. This study showed that in most cases the initial contact and impact were absorbed by a different body region in both the sagittal and the frontal position rather than head. Only three cases resulted in the primary impact being absorbed by the dummy's head first in the frontal plane, especially at relatively low impact speeds and with the older tram types (T3R.PLF and KT8D5). In the frontal impact, a contact with head occurred in all cases during the primary impact. In the case of side impact, a head contact only occurred at higher speeds with modern tram types (14T and 15T).

The study hypothesised that the shape and design of the body would have a major effect on the extent and severity of injuries, i.e., that the older models of the T3R.PLF and KT8D5 type, with a perpendicular front end, would result in more serious injuries (higher resultant head acceleration) than the modern curved front end designs of the 14T and 15T trams. However, our calculations did not confirm this assumption unambiguously. Only in one case, at a speed of 20km/h, the results showed a probability of a more serious injury caused by the oldest model of the T3R.PLF tram body.

The results of this study showed that regarding the primary impact, the resultant head acceleration, as well as corresponding HIC_{15} value, increased with higher impact speed for all tram types and collision scenarios in a similar way. However, the values were significantly higher in the case of frontal impact compared to side one, especially for a modern 15T tram type. The probability of serious/severe injuries (AIS3+ or AIS4+) did not exceed the value of 10 % for all tram types, speeds, and collision scenarios though. The results suggest that the primary impact of tram-pedestrian collisions might not cause any fatal head injuries within the range of 5-20km/h impact speeds. However, future studies could include more experiments for a robust and thorough statistical analysis, they could use other types of anthropomorphic test device to provide a biomechanical response of children and women during similar crash-test scenarios, and there could be an analysis of the following seondary impact of body with surrounding infrastructure. The future studies might be also interested in the influence of the front-end design and its properties on the collisions and their consequences.

5 Conclusion

The results of tram-pedestrian collisions, using an anthropomorphic test device, showed an increasing trend of resultant head acceleration and corresponding HIC_{15} values with higher speed for both, frontal and side impact. The values were higher in the case of frontal impact, and therefore there was a higher probability of more severe/serious head injuries. However, the probability of such injuries did not reach the value of 10 %, which suggests that the risk of serious/severe head injuries is low. The results also showed that tram-pedestrian collisions were very complex and complicated and they could be influenced by many factors (the collision scenario, impact speed, shape and design of tram front ends, properties of dummy and its position during impact, and the area of initial contact). The results suggest that the design of tram front ends and their mechanical properties could decrease the risk and severity of head injuries during the primary impact.

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