# Optimising the design of tramways to mitigate injury risk in pedestrian impacts

Toni Weber, Markus Muser, Kai-Uwe Schmitt

***Abstract*** Pedestrians often suffer severe injuries from collisions with trams. In most scientific studies, principle accident circumstances are investigated, but the optimisation of the tram front-end design is rarely addressed. Hence, the objective of this study was (a) to optimise the tram front-end design to reduce pedestrian injury risk and (b) to develop practical design guidelines for public transport services and manufacturers. Typical accident scenarios were defined based on an analysis of tram-pedestrian collisions in a major Swiss city as well as on cases reported in the literature. In the simulation environment Madymo, mathematical models of five different tram front geometries were tested against models of a 50$^{th}$ percentile and a 6-year old pedestrian dummy. Kinematics of the struck pedestrians were analysed and the injury criteria HIC, head acceleration and/or head impact velocity were compared. Particularly the primary impact was addressed, but the secondary impact as well as the situation where a pedestrian ends up underneath the tram was also investigated. Potentially critical areas in different tram front geometries such as the front cover, the windscreen, the a-pillars or the ground clearance were identified. Based on these findings, front-end design guidelines were established together with Swiss public transport services.

***Keywords*** pedestrians, tram front-end design, tram-pedestrian collisions, mathematical modelling

## I. Introduction

In the automotive industry, collisions of vehicles against pedestrians have been extensively addressed. Several measures, such as compliant bumpers, dynamically raised bonnets and windscreen airbags have been implemented to improve pedestrian protection in frontal collisions [1]. Investigations have shown that the vehicle front-end design, particularly the shape and stiffness of a vehicle front-end, as well as the impact velocity have a significant influence on the injury risk of pedestrians and cyclists (e.g. [2][3]). In this regard Lyons & Simms [2], for example evaluated the effect of a vehicle's windscreen geometry on pedestrian head injury and, amongst other proposals, it was suggested that a steeper windscreen angle is less prone to cause head injuries to pedestrians.

In the public transport sector this topic also has become more important since pedestrians and other vulnerable road users (i.e. cyclists) also suffer severe injuries from collisions with trams. According to a United Nations report on urbanisation [4], (in Europe and the USA) currently about one in two people lives in a city, and in only about 35 years, two out of three will. Hence, an increase in injured pedestrians is to be expected. The Swiss Council for Accident Prevention, for instance, reported 412 severely and fatally injured persons in tram collisions in Switzerland between 2003 and 2013. Almost 50% (n=203) were pedestrians and about 14% (n=57) were bicyclists, complemented by tram passengers, vehicle drivers, motorcyclists and others. The case fatality rate of non-motorised individuals injured in tram collisions was found to be 8.74% while it is only 0.96% in motorised individuals. Between 2003 and 2013 the number of severely injured persons in tram collisions varied to a great extent (i.e. between 14 in 2005 and 30 in 2012)[5]. However, there tends to be a slight overall increase.

In the context of tramway safety and the analysis of tram accidents to-date only few scientific studies are available. Mostly data from hospital statistics was analysed (e.g. [6][7][8][9][10][11]). Hedelin et al. [8], for instance, conducted a retrospective analysis of 209 tram accidents in Gothenburg (Sweden) in the years 1988 to 1992 including 193 non-fatal and 16 fatal cases. It was observed that in 48 % of all accidents with fatally injured

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pedestrians trams were involved, and that 60 % of the fatally injured were intoxicated with alcohol. 76 % of the pedestrians were injured and 69 % were killed near or at a tram stop. Moreover, persons who were overrun by a tram suffered the most severe injuries. The same data set was used in [9], but this time tram and bus accidents were compared. It was found that the risk of suffering non-fatal injuries per driven kilometre was four times higher in trams compared to busses, and that the risk of suffering fatal injuries was even 9-15 times higher in trams. Furthermore, all fatally injured were found to be pedestrians.

Based on a literature review on tram accidents in Melbourne (Australia), Grzebieta & Rechnitzer [12] simulated tram-car collisions as well as tram-pedestrian collisions and proposed a method to optimise the tram front-end design. Two tram fronts were implemented in Madymo colliding against a standing Hybrid III dummy as well as against the side of a car with a EuroSID dummy as occupant. HIC and VC were assessed and compared to reference values. The impact velocity was chosen to be 35 km/h. It was found that in both, tram-car and tram-pedestrian collisions, HIC values dropped (significantly) when a padded under-run barrier or front trim panel was added. However, it was also stated that the mitigation of injuries for the car side impact crash is in conflict with mitigating pedestrian impact injuries. Because of the under-run barrier the pedestrian rotates around the thigh and suffers a head impact at the tram front. Hence, a variation of the padding properties was proposed. Also Hyncik et al. [13] conducted computer simulations with a model of a Czech tram striking (a) a $50^{th}$ percentile male as well as a scaled 6-year old child dummy model and (b) impacting another tram. Injury risk in struck pedestrians as well as in the tram driver and passengers was observed by calculating HIC and TTI. A bumper was implemented at the front of the tram and varied in a horizontal and vertical direction to investigate differences in pedestrian injury risk. Moreover, different bumper materials were tested with respect to injury risk in driver and passengers. For a struck adult pedestrian it was suggested to locate the bumper at a very low position sticking out of the tram face. In contrast, for the struck child pedestrian the highest possible position was suggested. Anghileri et al. [14] investigated the crashworthiness of an Italian tram type according to EN 15227 and UNI 11174 respectively by use of mathematical modelling. Here the focus was set on driver and passenger safety. It was found that the tram type generally fulfilled the European crashworthiness requirements. However, an additional scenario (not specified in EN15227) was tested and therefore three front-end structural enhancements as well as a new "seat push-back system" for the tram driver were developed. It could be shown that injury risk in passengers and driver could be reduced by implementation of these measures.

In 2001 a European research project ("SAFETRAM") was initiated primarily addressing cost-effective improvements in passive safety of tramway vehicles, which included structural and interior design rules contributing to a safe environment for occupants during crash events ([15][16]). Furthermore, in 2011 another European research project on tramway safety ("COST TU1103 – Operation and safety of tramways in interaction with public space") was started. This project ends in 2015 and so far results of the working phase 1 are available [17]. The overall aims are to improve "light rail transit" (LRT) safety and road safety in general, to minimise negative impacts on level of service and to reduce operational costs.

Taking into consideration the results of the accident analysis studies, the approach of the simulation studies as well as the European research projects on tramway safety as described above, there seem to be research gaps in the context of tram-pedestrian collisions. Hence, the objective of the study presented in this paper was to reduce the pedestrian injury risk by optimisation of tram front-end design. The primary impact was particularly addressed, but the secondary impact was also taken into consideration. In a joint discussion together with representatives of four Swiss public transport services, various approaches contributing to mitigate the injury risk of pedestrians were defined and formulated in a publically available consensus paper. This paper now serves as a guideline for public transport services and/or manufacturers intending to acquire or rather develop new vehicles or optimise a currently existing vehicle fleet.

## II. METHODS

In order to define technically feasible front design recommendations for trams, three different approaches were pursued: accident analysis, mathematical modelling and an expert discussion. These methods complement each other and allow efficient practical implementation of the recommendations developed. By analysing accidents, typical accident circumstances, scenarios and patterns were investigated. Mathematical modelling served to evaluate the injury risk of a struck pedestrian to identify potentially critical areas in different tram types. In the expert discussion, basic (design) approaches were evaluated and critically reviewed taking operational aspects into consideration.

### *Accident analysis*

Besides an extensive literature review as presented above, 67 tram accidents with pedestrians and bicyclists which occurred in a major Swiss city in the years 2009, 2010 and 2011 (1st half) were analysed to gain insight into the accident situation and to identify typical accident scenarios and patterns. The analysis was based on data of the "Police Information System" (POLIS) database, i.e. the police database with information such as major incidents, unusual deaths or suicide attempts, as well as on police reports of urban police forces. 29 accidents involving severely or fatally injured pedestrians and bicyclists were chosen from the POLIS database. In the accident analysis only accidents in which a person was struck frontally by a driving tram were included; four unusual cases (i.e. a person falling while trying to jump on a waiting tram) were excluded. As a control group, 38 cases with uninjured or slightly injured pedestrians were investigated; here one unusual case was excluded. Accidents with uninjured or slightly injured bicyclists were not considered.

### *Mathematical modelling*

Computer models of four different tram front geometries currently in use as well as of one "virtual" tram front were built and multi-body simulations were performed. The surface models of two tram fronts circulating in Swiss cities were generated from 3D-scans, and two further models were generated using existing CAD data. The "virtual" tram front was built at a later state taking the results of the simulations with real tram fronts into consideration; basically a completely new shape was applied by adding or rather removing structural parts of an existing tram front (see Fig. 3). The CAD representation of all tram fronts was simplified using the software Kubotek KeyCreator version 9.0.3/10.0.0. The tram front models were meshed (mesh type: trias (2D), element size: 2-3 cm) with the pre-processor software Gmsh version 2.8.4 and Csimsoft Trelis version 14.0.2. The 2D mesh-models were then implemented into the simulation software Madymo version 7.3 [18][19]. All front-end parts including the windscreen were modelled as rigid bodies. Modelling of the tram underbodies was done manually using rigid planes. The road surface was modelled as a plane as well, using a friction coefficient of 0.6. In the accident analysis it was observed that most pedestrians were struck by a tram when trying to cross the street from the right to the left. Thus, similar to [12], a standing 50th percentile pedestrian human model was placed in a corresponding position in front of the trams. As in [13], additional simulations were run with a human model of a 6-year old child [20]. Moreover, it was investigated that most accidents occurred at or near tram stops. Hence, impact velocities were chosen to be 10, 20 and 30 km/h. In this context Luttenberger et al. [21], for instance, investigated future pedestrian accident scenarios (involving next decade small electric vehicles) primarily employed in urban areas in 2025 and it was estimated that the most frequent impact velocity would be between 10 and 30 km/h. The accident analysis also showed that an emergency braking was initiated in practically all investigated cases. Therefore, in the simulations four trams (Type A-C and E) were constantly decelerated with 2.9 $m/s^2$ and one tram (Type D) was decelerated with 2.7 $m/s^2$ between 30 km/h and 15 km/h and with a linearly increasing deceleration from 2.7 to 3.3 $m/s^2$ between 15 and 0 km/h. The deceleration values were provided by the public transport services. The results of a total of 31 simulations will be presented in the following paragraphs. In 12 runs, a 50th percentile dummy and in another 12 runs a 6-year old dummy is struck by the original tram fronts. In an additional three runs, a 50th percentile dummy is struck by the "virtual" tram front, and in four additional simulations a 50th percentile dummy is struck by modified tram fronts (only type A&C). The modification was realised by forward displacement of the front trim panel of about 8 cm relative to the windscreen. In Table 1 an overview of the computer simulations conducted is given.

For the assessment of the injury risk, primarily kinematics were analysed and the head acceleration at the impact (in $m/s^2$), the impact speed of the head normal to the struck surface (in m/s) as well as the head injury criterion (HIC) were calculated. The head acceleration was determined at the time points when the head of the pedestrian struck the front surface and the ground. The 3 ms criterion ($a_{3ms}$) was chosen as a basis for evaluation.

Table 1
Overview of the simulations conducted for five different tram types A-E.

| Tram type | A (original & modified) | B (original) | C (original & modified) | D (original) | E (virtual) |
|---|---|---|---|---|---|
| Dummy model | $50^{th}$ percentile and 6-year old pedestrian | | | | $50^{th}$ percentile pedestrian |
| Impact velocity | 10, 20, 30 km/h | | | | |
| Posture | standing in front of the tram | | | | |

The impact velocity was calculated at the time of the impact using the following equation:

$$v_A = (v_{Kx} * \cos(\alpha) + v_{Kz} * \sin(\alpha)) - (v_{Tx} * \cos(\alpha))$$

where $v_{Kx}$ and $v_{Kz}$ are the velocities of the head in x- and z-direction, $v_{Tx}$ is the tram velocity in x-direction and $\alpha$ defines the angle of the struck surface relative to the horizontal.

For the calculation of HIC the following equation was used:

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

where $t_1$ and $t_2$ are any two arbitrary time points during the acceleration pulse and $a$ is the resultant acceleration [22].

No threshold values were applied, but the calculated injury criteria values (as presented in Table 3) were compared to investigate differences in the performance of the different tram fronts. In Fig. 1 the mathematical model implemented in Madymo is illustrated for one of the simulated tram fronts.

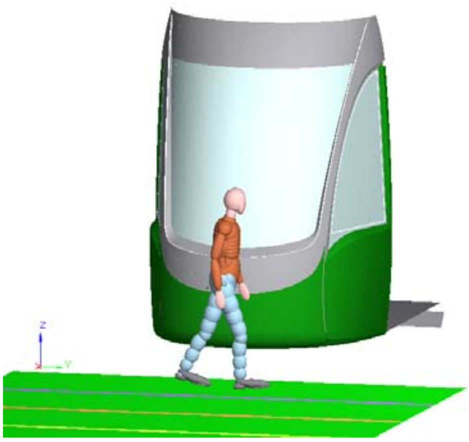

Fig. 1. Mathematical model of a pedestrian struck by one of the simulated tram fronts (Madymo).

***Expert discussion / Consensus paper***

Using the basic principles of the Delphi method [23], experts were invited to discuss operational and manufacturing aspects with regard to specific design recommendations. Together with representatives of four Swiss public transport services who run tramways, the results of the accident analysis and computer simulations were discussed. Furthermore, first approaches towards the optimisation of the tram front-end design were introduced. The representatives' input was then used to improve and change certain design recommendations. Afterwards, the approaches were tested in additional computer simulations to verify their potential, and eventually all design recommendations were formulated in a consensus paper.

## III. RESULTS

### *Accident analysis*

In a major Swiss city, between 2009 and 2011 (1st half) most pedestrians and bicyclists involved in tram collisions were situated close to tram stops and crosswalks. 18 (of 25) severely and fatally injured persons were hit close to the centre of the tram front structures when trying to cross the tracks from the right side; six persons were hit while crossing from the left side. Lack of attention or rather carelessness was found to be the leading cause of the accidents. After the primary impact to the front-end structure of the trams, nearly all persons suffered a secondary impact on the ground or kerb. Pedestrians were typically struck in a standing or walking position. In 21 cases head injuries were observed, however, it was not always possible to evaluate whether the injury occurred in the primary or secondary impact. Clear evidence, such as marks on the windscreen or broken front structures, were only found in a few cases. In all investigated accidents, the emergency brake was activated before the impact. Moreover, in five cases the pedestrians were thrown forward, suffered a secondary impact on the ground and were then partially overrun by the tram. These persons did not suffer additional injuries from being overrun as there was enough ground clearance underneath the tram front-end structure. The investigated cases did not show any person struck by the wheels. Nevertheless, two cases were observed in which a contact with structural parts of the front-end (i.e. lateral longitudinal members) led to serious head injuries. The investigation of accidents with uninjured and slightly injured pedestrians showed that the accident circumstances were basically similar compared to those of the severely and fatally injured. However, head injuries were only documented in two (of 37) uninjured and slightly injured pedestrians compared to 17 (of 20) in severely and fatally injured pedestrians. In Table 2 an overview of the investigated cases with severely and fatally injured persons is given.

### *Mathematical modelling*

In Table 3 the results of 31 simulations are presented. In almost all scenarios with the original front-ends a primary impact at the tram front and a secondary impact at the ground were observed. However, in tram types A and D, at the lowest impact velocity no head contact at the tram front was registered. For the primary impact the calculated injury criteria values were found to be comparably low at impact velocities of 10 and 20 km/h in all tram types. At the highest impact velocity (30 km/h), however, in three out of four tram types (A, C and D) the risk of suffering a severe head injury in the primary impact increases clearly.

As can be seen in tram types C and D a pedestrian may suffer a severe head injury in the secondary impact already at the lowest impact velocity (10 km/h). In tram type A, a severe head injury in the secondary impact is assumed at 20 and 30 km/h. However, in this regard in tram type B the injury risk is high at 20 km/h, but at 30 km/h it is comparably low.

In the simulations with the modified tram types A and C a reduced injury risk was observed compared to their original version. This, however, only holds true for the primary impact. In the modified tram type C a comparably low injury risk was found at 10 km/h; at 20 and 30 km/h, however, the injury risk is basically similar compared to the original version (only regarding secondary impact). The performance of (virtual) tram type E was found to be similar compared to the modified tram type C.

For the 6-year old pedestrian the risk of suffering a severe head injury from the primary impact is low at 10 km/h in all tram types. Only in tram type A the injury risk is still low at 20 km/h and in the other tram types the injury risk noticeably increases at 20 and 30 km/h. In tram types A, C and D a high risk of suffering a severe head injury in the secondary impact is assumed. In tram type B, however, at impact velocities of 20 and 30 km/h the injury risk was found to be surprisingly low.

Table 2
Investigated cases with severely and fatally injured persons conducted in a major Swiss city.

* The accident was regarded as "unusual case" and thus excluded from the analysis.

| **Year** | 2009 - 2011 (1st half) |
|---|---|
| **Persons involved** | - 29 cases including 19 severely and three fatally injured pedestrians as well as five severely and two fatally injured bicyclists |
| **Accident causation** | - 18 cases: violation of the tram precedence<br>- other cases: acute-angled crossing for cyclists, wrong behaviour at traffic lights, disregarding red lights, violation of right of way, distraction, lack of attention, medical factors, misconduct bicycle/moped |
| **Accident circumstances** | Severely injured:<br>- 17 pedestrians were struck by a tram when trying to cross the tracks (10 at a tram stop, four at a crosswalk, two on the road and one unknown)<br>- three bicyclists were struck by a tram when trying to cross the tracks<br>- one pedestrian got off the tram and was hit by the rear-end of the departing tram*<br>- one pedestrian fell and hit the tram at the side with his/her head*<br>- one bicyclist overtook the tram, was slightly hit, fell and was struck by another vehicle*<br>- one bicyclist adhered at the left side of a tram; he/she fell when an oncoming tram approached*<br>Fatally injured:<br>- three pedestrians were struck when trying to cross the tracks (two were hit on a crosswalk - one in a stooped posture - and one was pushed away after being struck)<br>- one bicyclist was struck and overrun by a tram when trying to turn across the tracks<br>- one bicyclist fell onto the tracks and was struck by a tram |
| **Summary** | - 25 cases with impacts at tram fronts<br>- most pedestrians were pushed away after being struck by a tram<br>- one pedestrian was struck by a tram in a stooped posture, all others were standing/walking<br>- head injuries were most common<br>- two pedestrians were overrun by a tram<br>- one bicyclist fell and was struck by a tram while lying on the ground, the others were struck in front of a tram |

Furthermore, it was investigated whether a struck pedestrian was overrun by a braking tram after the primary and secondary impact. Tram type B and E are equipped with an overrun protection device hence, it is not possible to run over the pedestrian at any impact velocity. In this case the pedestrian is hit by the overrun protection device and pushed forward in front of the tram until the tram comes to a full stop. In the other tram types (A, C and D), the 50th percentile pedestrian is not or only partly overrun (i.e. only the limbs or the head is underneath the tram) at impact velocities of 10 and 20 km/h. At 30 km/h, however, the 50th percentile pedestrian is completely overrun (i.e. the whole body is underneath the tram) by all three tram types. In contrast, the 6-year old pedestrian is completely overrun by all tram types (except type B, see explanation above) already at 20 km/h. At 10 km/h the 6-year old pedestrian is not overrun by any tram type.

In computer simulations with the five different tram front geometries A-E it was shown that pedestrians who sustain a head impact against the windscreen or against other front-end structural parts encounter a serious injury risk. Furthermore, stiff protruding structural parts underneath the tram front may also increase the injury risk for a person being overrun. Potentially critical parts and areas in the different tram front-end designs could however, be identified. In Fig. 2 the primary and the secondary impact of a pedestrian struck by one of the simulated real tram fronts as well as by the "virtual" tram front are illustrated.

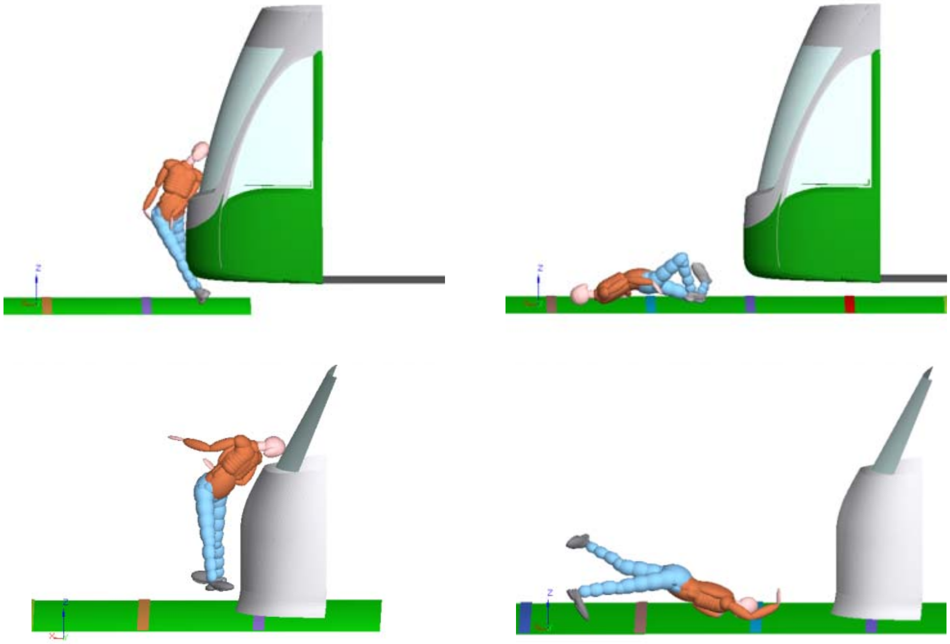

Fig. 2. Pedestrian-tram collision at 30 km/h: The 50th percentile pedestrian human model is struck by one of the real tram fronts (top) and by the "virtual" tram front (bottom). Left: primary impact, right: secondary impact.

Table 3
Results of the mathematical modelling.

* The front trim panel was displaced forward about 8 cm relative to the windscreen.
IV: impact velocity, HIC: head injury criterion, HIV: head impact velocity, HA: head acceleration, P: primary impact, S: secondary impact, NHC: no head contact

| **Tram type** | | A (original) | | | B (original) | | | C (original) | | | D (original) | | | E (virtual) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dummy** | | | | | | | | 50th percentile | | | | | | | |
| **IV [km/h]** | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 |
| **HIC P** | NHC | 190 | >5000 | 26 | 61 | 192 | 100 | 377 | 1537 | NHC | 75 | >5000 | - | - | - |
| **HIC S** | 13 | 3407 | 1810 | 103 | 3111 | 470 | 4048 | 4100 | 741 | 1219 | >5000 | >5000 | - | - | - |
| **HIV P [m/s]** | NHC | 6.2 | 4.8 | - | - | - | 1.7 | 2.1 | 3.5 | NHC | 2.6 | 1.2 | - | - | - |
| **HIV S [m/s]** | 0.6 | 4.8 | 3.6 | - | - | - | 3.4 | 2.7 | 1.6 | 2.1 | 3.2 | 7.3 | - | - | - |
| **HA P [m/s$^2$]** | NHC | 610 | 759 | 270 | 206 | 404 | 283 | 701 | 955 | NHC | 526 | 351 | - | - | - |
| **HA S [m/s$^2$]** | 289 | 733 | 523 | 150 | 646 | 299 | 643 | 605 | 1081 | 382 | 766 | 1770 | - | - | - |
| **Tram type** | | A (modified*) | | | B | | | C (modified*) | | | D | | | E (virtual) | |
| **Dummy** | | | | | | | | 50th percentile | | | | | | | |
| **IV [km/h]** | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 |
| **HIC P** | - | - | 243 | - | - | - | NHC | 91 | 307 | - | - | - | NHC | 287 | 604 |
| **HIC S** | - | - | - | - | - | - | 323 | 3937 | 1472 | - | - | - | 506 | >5000 | >5000 |
| **HIV P [m/s]** | - | - | 1.7 | - | - | - | NHC | 1.4 | 1.6 | - | - | - | NHC | 0.2 | 2.2 |
| **HIV S [m/s]** | - | - | - | - | - | - | 0.9 | 3.1 | 1.9 | - | - | - | 1.2 | 5.2 | 5.3 |
| **HA P [m/s$^2$]** | - | - | 742.5 | - | - | - | NHC | 238 | 445 | - | - | - | NHC | 193 | 1177 |
| **HA S [m/s$^2$]** | - | - | - | - | - | - | 408 | 768 | 367 | - | - | - | 356 | 576 | 1325 |
| **Tram type** | | A (original) | | | B (original) | | | C (original) | | | D (original) | | | E (virtual) | |
| **Dummy** | | | | | | | | 6-year old | | | | | | | |
| **IV [km/h]** | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 |
| **HIC P** | NHC | 362 | 2968 | 244 | >5000 | >5000 | 190 | 891 | >5000 | NHC | 1830 | >5000 | - | - | - |
| **HIC S** | 3027 | >5000 | >5000 | 1466 | 13 | 79 | 4575 | 2626 | >5000 | >5000 | >5000 | >5000 | - | - | - |
| **HIV P [m/s]** | NHC | 1.4 | 3.0 | - | - | - | 1.5 | 2.7 | 4.2 | NHC | 2.4 | 2.0 | - | - | - |
| **HIV S [m/s]** | 4.3 | 5.3 | 5.4 | - | - | - | 3.1 | 2.5 | 4.8 | 3.5 | 7.0 | 6.3 | - | - | - |
| **HA P [m/s$^2$]** | NHC | 276 | 511 | 351 | 616 | 908 | 345 | 386 | 346 | NHC | 247 | 358 | - | - | - |
| **HA S [m/s$^2$]** | 347 | 735 | 1055 | 406 | 69 | 99 | 627 | 536 | 888 | 579 | 721 | 1069 | - | - | - |

***Expert discussion / Consensus paper***

The recommendations specified below were defined together with representatives of four Swiss public transport services who use tramways. As a result, a consensus paper was written which now serves as a guideline for public transport services as well as manufacturers planning to improve pedestrian safety in currently existing tram fleets or new tram front-end geometries. Considering operational and manufacturing (implementation) aspects the following recommendations were formulated in the consensus paper:

1) *Protruding parts* as well as sharp edges can increase the injury risk of a struck person significantly even at lower impact velocities since impact forces at edges are applied to the body over a small area. Hence, such parts and edges must be avoided wherever an impact is possible. Wiper axes must be positioned behind the front cover or covered adequately.

2) The *a-pillars* should be designed in order to be able to damp a head impact. Therefore the application of a soft material would be appropriate. Sharp edges should generally be avoided in this area, or at least exhibit a minimal radius of 10 mm. In this context the tram driver's field of view must not be affected in any way.

3) As *windscreens* of trams must be designed with a much higher stiffness as e.g. car windscreens, they will not break under a head impact. Therefore, the only possible measure is to avoid the head impact or at least reduce the impact velocity of the head as far as possible. This can be achieved by either increasing the inclination angle of the windscreen or by increasing the horizontal distance between front trim panel and windscreen. The measure described here is particularly aimed at adults in a standing or rather walking position, however, depending on the design of the tram front this measure could also be advantageous for children. Additional space gained by the forward displacement of the front trim panel relative to the windscreen could be used for energy absorption to minimise the injury risk for the pelvis and the thorax. In Fig. 3 the recommendations described above are illustrated.

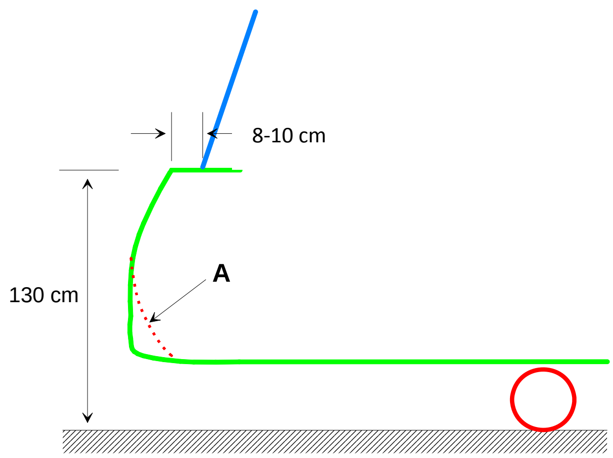


Fig. 3. If the front trim panel is displaced forward relative to the windscreen by about 8-10 cm, the pedestrian will contact the tram initially with the pelvis or the upper body only. As these body parts are already accelerated at the point in time when the head impact occurs, the head impact velocity is reduced or the head impact is avoided completely. The lower edge of the windscreen must not be positioned lower than 130 cm and the use of an almost vertical contour for the lower part of the front trim panel is suggested. Particularly for children a round shape (A) would apply a force that would accelerate the body towards the ground and, thus, increase the injury risk at the secondary impact.

4) On the one hand, the *ground clearance* of the tram front should allow a partial overrun of a person lying on the ground. On the other hand, any trapping of body parts by protruding structural parts must be prevented. Any contact between the body and the wheels must be avoided. If the tram exhibits a ground clearance sufficiently high to overrun a person lying on the ground without crushing the person, this must be ensured by e.g. structural parts positioned closer to the ground (Fig. 4, C) in order to prevent such a contact with the

wheels. For the specification of the necessary ground clearance, the diameter of a 50th percentile adult male head was chosen as a starting point. The front trim panel of the tram must thus have a ground clearance of at least 25 cm (fully loaded). Close to the wheels, a profile lowered to 5-8 cm above the ground (depending on the wear of the wheel) and extended across the entire width of the vehicle should be implemented to prevent wheel contact. The (operator specific) predetermined minimal ground clearance must not drop below 5 cm at any loading or wheel wear status of the tram. Whether flexible structural parts may be positioned lower than 5 cm needs to be further evaluated.

5) The *available space under the tram front* should be designed as homogeneous as possible, i.e. no potentially dangerous structures should be located in the lower anterior part of the front trim panel. This particularly refers to edged carrier structures (e.g. load-bearing members) or components such as couplings. Additionally, it is suggested to cover the entire space below the tram front with a panel (e.g. sheet metal) in order to avoid any further contact with protruding structures.

6) *Overrun protection devices* can reduce the gap between device and ground to practically zero. Nevertheless it must be ensured that the device is effective across the entire width of the vehicle. Furthermore, special attention must be paid to the positioning and the release mechanism. Also at higher velocities the device must be released accordingly to be in position in due time, and it must not exhibit any potentially dangerous design features (e.g. sharp edges, stiff materials). Such protection devices should be positioned as far back from the front-end as possible in order to guarantee low impact velocities for overrun persons. They must be located in front of the first set of wheels, far enough to prevent a person's limbs from contact with the wheels.

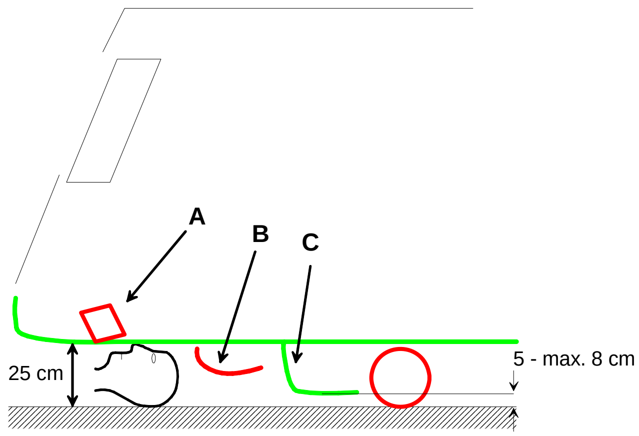


Fig. 4. Structural parts positioned above a height of about 25 cm above the ground (A) can cause injuries if a person e.g. rotates under the tram. Structural parts located higher than 5-8 cm but lower than 25 cm above the ground (B) can cause injuries by direct impact, but also by e.g. trapping or crushing. Any contact with the wheels must be avoided. Thus, a movable or fixed, preferably soft-covered profile positioned about 5-8 cm above the ground (C) can prevent a contact to the wheels.

## IV. DISCUSSION & CONCLUSION

Through analysis of real world accidents and existing literature, typical tram-pedestrian collision scenarios and patterns were identified. The accident analysis revealed that trams most often strike pedestrians at or close to tram stops. This is in line with the findings of e.g. Hedelin et al. [8]. Moreover, lack of attention was found to be a leading cause for tram-pedestrian collisions. Public transport services already introduced gates, safety railings (as also stated in [8]) and other collision prevention systems however, particularly at tram stops it remains difficult to find appropriate measures, keeping in mind the existence of several structural restrictions. In terms of mitigating injury risk in pedestrians an alternative or rather additional measure is the optimisation of the passive safety of tramways. The development of design principles for an optimised or new tram front-end design was therefore addressed in this study.

Regarding the results of the accident analysis it must be considered that the accident circumstances investigated might not be representative for other Swiss or European cities, since accident occurrence was only analysed in one Swiss city. Besides, it might be regarded as a limitation that police reports primarily exist for collisions with severely or fatally injured persons and there might be no or significantly fewer reports for collisions with uninjured or slightly injured persons. Furthermore, the classification of injury severity in this study was based on the classification of injuries taken from police reports, i.e. any hospitalised person was regarded as severely injured. The analysis showed that the injury severity was over-estimated in some cases. Nevertheless, tram-pedestrian accident circumstances generally seem to correlate among European cities as can be seen when comparing the results of this study with [6][7] or [8].

The front-end design of four trams currently in use in different (Swiss) cities were tested in computer simulations and compared to optimised tram fronts as well as to a "virtual" tram front. It could be shown that the primary impact can be affected in a positive way by application of relatively simple changes such as forward displacement of the front trim panel relative to the windscreen. Lyons & Simms [2], for instance, observed a positive effect on pedestrian head injury risk in collisions against cars by changing the windscreen angle, coefficient of friction and/or the windscreen stiffness. Unfortunately, this measure cannot be transferred to trams since regulations (i.e. similar to high-speed train regulations) prohibit any changes in currently used tram windscreens. The windscreens of trams are thicker and stiffer compared to those of cars, and do not break under the impact conditions discussed here, thus, in the simulations the material was rigid. Also the material of the front trim panel was rigid since a tram front-end is not as yielding as a car front-end. Hence, material properties were not modified which might be regarded as another limitation. Changes in other structural parts were possible and, thus, particularly the front-end shape was addressed. However, the corresponding recommendations given here complement the approaches of comparable studies such as [12] and [13].

At impact velocities below 30 km/h also the secondary impact must be considered. It was shown that already at the low impact velocity of 10 km/h a pedestrian may suffer severe head injuries from the secondary impact. The secondary impact is less dependent on the collision speed, but is subject to many factors difficult to quantify.

In tram-pedestrian collisions, struck pedestrians are usually thrown in the driving direction of the tram and may be overrun by the tram while it is still braking. To prevent pedestrians from suffering additional injuries in such a situation, recommendations addressing overrun protection devices were proposed. Additional recommendations regarding protruding parts, the a-pillars or ground clearance were developed and are essential in order to reduce the injury risk. The design approaches were diversified to the greatest possible extent to be transferable to a variety of trams. All recommendations were defined in co-operation with representatives of public transport services by considering also operational aspects. A consensus paper was developed which now serves as a guideline for trams to be optimised or developed in the future. The feasibility of the individual measures has to be further evaluated taking into account sometimes competing basic requirements such as design measures with respect to crash standards, the mobility of the vehicle coupling, the ground clearance in sag-and-summit trips or the field of view of the tram driver. Such difficulties arise in particular where the modification of currently existing vehicles is concerned.

As already stated above, there are various factors such as regulations or design and operational requirements limiting the mitigation of the injury risk of pedestrians in collisions against trams. By including the recommendations of the consensus paper into their design input requirements, the operators of Swiss trams have however, taken important steps towards this goal.

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