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Pedestrian fatality risk as a function of tram impact speed

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Abstract: The objective of the presented research-work was to develop a model to describe the risk of fatal accident involving tram and pedestrian. This study extends research concerning relationships between the “impact speed” and probability of pedestrian death in case of tram accident. Over 400 “tram-pedestrian” accidents were analyzed. Logistic regression analysis was used in these studies. The main objective of the research is to compare the risk of fatal accidents when pedestrians are struck by passenger cars and trams. GPS system from trams is used to analyze correlation between the tram speed and different conditions along the public transport stop areas (e.g. traffic signals, priority, and platforms localization). The results show that the fatal risk of hitting pedestrians by a tram running at a speed of 50 km/h is two and a half times greater than that by a car. Research clearly proves that comparing to car impact speed, there is much higher probability of death when pedestrian is hit by a tram running at a speed of 30 km/h – almost 40% (compared to 5% when hit by car). There are even cases of deaths with a very low speed of tram (5–10 km/h).

Keywords: public transport, fatality risk, speed, pedestrian safety

1 Introduction

Death of pedestrians and cyclists represent 26% of world traffic deaths [1], with highest rate mostly in low-income countries, where more vulnerable road users (VRU) are killed at roads more frequently than car occupants. Poland

belongs to the EU countries with the largest risk of death and serious injuries among pedestrians, with 26.8% share in all deaths [2].

Although majority of known research is focused on road safety, due to the revival of the tram network in many cities around the world, it is very important to expand knowledge about safety relationship between the speed of light rail and consequences of the collision with VRU. It can be expected that promoting sustainable transport will result in an increase in both tram traffic and foot traffic. Thus, the frequency of conflicts between them will increase.

Trams are 12 times more likely to be involved in an accident than a car on each passed kilometer [3]. Urban rail systems are highly risky for pedestrians. The authors' research in Krakow shows that pedestrians constitute 62% of all fatalities and are seriously injured in accidents involving buses and trams. Similar conclusion might be found in French National Report on Accidentology of Tramways [4].

High-risk areas are public transport (PT) stops where pedestrians are often more preoccupied with the departing tram or bus than with other vehicles crossing their paths. One of the most dangerous spots for pedestrians and cyclists are pedestrian crossings. Haste, crowds, and obstacles increase the likelihood of accidents, while the size and shape of the front of PT vehicles make stronger the consequences of hitting a pedestrian.

According to author's own research taken in Krakow, 83% of fatal or serious accidents with trams and pedestrians were at PT stops or pedestrian crossings. Similar situation can be observed in other Polish cities, with the percentage mostly between 50 and 70%.

Although the number of accidents involving trams is comparatively very limited to the total number of road accidents, the consequences of tram crashes are very serious, especially when pedestrians are run over. The new power supply technologies (e.g. catenary-free systems) allow to build tram networks, even in old town centers and pedestrian areas, with additional increased risk of pedestrian casualties. This will require specific design solutions and traffic regulations for road safety [5,6].

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Cities around the world reconstruct their transport infrastructure, sometimes taking experiments with new ideas, such as shared spaces or Tempo-30 zones with tram and bus traffic. Therefore, knowledge of “safe speeds” of PT vehicles is essential to avoid infrastructure errors that may result in death and serious injuries. On the other hand, light rails around the world are one of the key transport modes within the sustainable mobility, thus their speed and the ensuing from this time travel should not be low. Therefore, the speed limit values for trams in “vehicle – pedestrian” conflict areas should be reasonable, i.e., determined as a compromise between pedestrian safety and acceptable travel time in the tram. Pedestrian safety can be described by the risk of fatality in case of being hit by a tram.

A factor used to describe the risk of fatal accident involving a vehicle and pedestrian is called an “impact speed.” It describes the relation between the vehicle speed in the moment of collision with the pedestrian and the consequences for the VRU.

In recent years, mathematical models including indirect measures are being developed for safety research, including speed [7–9]. These studies are mostly focused on the safety in car traffic; however, their conclusions can be applicable also in case of safety analyses of traffic with trams.

Surrogate measures in road safety are increasingly being used in planning and design practice. They enable a proactive approach to create a safe infrastructure. However, this requires prior quantification of the quantitative relationships between the selected indirect measures and road traffic risk. One of the most frequently used indirect measures in road safety are speed and its dispersion. This is due to the obvious relationship between the speed and consequences of accidents and the ease of collecting speed data from various vehicle traffic monitoring devices. Big data with the speed recorded online is more and more available. Based on this data, one can quickly implement and easily correct actions to reduce the risk of accidents. Taking into account the advantages of indirect measures of traffic safety, the authors undertook their own research, setting the following goals:

- quantification of the impact of tram speed on the risk of fatal “tram-pedestrian” accidents and comparison of this impact with that of car speed on the risk of fatal “car-pedestrian” accidents;
- evaluation of possible application of tram speed management as a means of improving pedestrian safety;
- preliminary analyses of the use of big data related to speed and its variability in identifying places of high risk.

Impact of car speed on severity of accidents involving pedestrians is well recognized [10,11], but there is a lack of similar data concerning trams and light rail vehicles operating on streets. Impact of tram speed on severity of accidents involving pedestrians can be indeed analyzed using simulation models [12]; however, the verification would require data collected in real traffic. Studies carried out by the authors of this work could be useful for this purpose.

This article presents the results of the authors’ research who used 10-year databases of the two largest Polish tram operators in Warsaw and Krakow. The conducted research clearly shows that there is a large difference in the above-mentioned influence of speed on the effects of trams colliding with pedestrians, compared to collisions between cars and pedestrians. The front of the tram does not deform as easily in the event of a collision as it does on a car. Therefore, the comparison of the impact of speed on the effects of a collision of a pedestrian with a tram and a car is reasonable and can be used as an indirect measure of traffic safety assessment.

Moreover, the article presents the possibility of practical application of the described relation between impact speed and fatality risk. The results presented in the article can be used, for example, to assess the pedestrian infrastructure scenarios in conflicting zones with trams, as well as to support decisions on introducing speed limits for trams in these zones. Knowing the impact of tram speed on the risk of fatal “tram-pedestrian” accidents, it will be possible to more rationally set speed limits using risk models. The value of speed limits should be equal or lower than the impact speed in the event of a tram hitting a pedestrian and correspond to the probability of fatal “tram-pedestrian” accidents smaller than considered as acceptable in the given conditions, e.g. 5%.

2 Impact speed as a surrogate measure of the risk of accidents involving pedestrians

Results of studies regarding the impact of car speed on the probability of pedestrian fatality risk have been summarized in previously published works [10–12]. One study [11] shows a summary of results as curves describing the probability of pedestrian fatality risk in relation to the impact speed (Figure 1). It is a representation of results from 15 studies carried out in 1980–2015, and multiple factors and limitations, such as lack of information about

Figure 1: Plot for S-shaped curves for pedestrian fatality risk by impact speed [11].

the victims' ages, car type etc., need to be considered when interpreting this data. There are likely factors other than impact speed that influence the risk of a pedestrian fatality or serious injury such as age, vehicle type, the response time of emergency assistance, and characteristics of the roadway design.

Many studies are focused on the assessment of sensitivity to the effects of age of the pedestrian hit by a vehicle at different speeds. The multivariate model described in ref. [13] highlights the fragility of the elderly in the age group of 60–74 years, especially above 75 years. This fragility can be seen as impact speed of 30 km/h up to 50 km/h, with the risk of death increasing 2-fold for pedestrians in the age group of 60–74 years and 7-fold for over 75 years as compared to pedestrians in the age group of 15–59 years. Speed of above 80 km/h is the overwhelming risk factor.

Considering these restrictions, the authors of the study stated that the risk of a fatality reaches 5% at an estimated impact speed of 30 km/h, 10% at 37 km/h, 50% at 59 km/h, 75% at 69 km/h, and 90% at 80 km/h [11].

It is a strong argument for a consideration of shared space streets or Tempo-30 zones implementation, as there is only 0.05 probability of death with impact speed less than 30 km/h.

However, it is not so obvious when one considers the risk of death in the case of hitting a pedestrian or cyclist by tram or bus. Such a situation should be classified as a heavy vehicle (HV) – VRU accident, the higher probability of which is described in literature [14,15], but a function of impact speed for HV similar to the one in ref. [11] is not found.

One can assume, in the case of “tram – pedestrian” crashes, that the age of the pedestrian can also have an impact on the risk of a pedestrian fatality, similar to “car – pedestrian” crashes. This impact may be limited in the case of speeds lower than 20 km/h. This should be mentioned due to the fact that the speed of the tram in conflict zones with pedestrians is often reduced to 20–30 km/h. In such cases, the impact speed may be significantly lower than 20 km/h because of a tram braking maneuver.

The problem of VRU is also discussed in another study [5], where it is stated that tram transportation system in the urban context poses numerous problems, still unsolved to some extent, for the road safety and safeguard of VRU (cyclists, pedestrians, and disabled people), especially at road intersections which are intrinsically very critical areas, both in terms of functionality and safety. The risk of accidents can be reduced e.g., by traffic management means, including speed management. Therefore, it is paramount to estimate the limit value of the relatively safe speed of a tram in conflict zones with pedestrian traffic.

Candappa et al. [16] compared different tram speeds and kinetic energy transferred to car when hit during the U-turn manoeuvre. The most important fact that car and tram distances required to bring the vehicle to stop are completely different was described in detail. One can mention that car and tram require approximately 31 and 50 m, respectively, to stop when moving with a speed higher than 50 km/h. The mass and speed of the two vehicles lead to two variability recommendations: physical separation of the two conflicting movements through the closure of median openings or grade-separation; or the strategic reduction of posted speed limits of trams at specific locations to maximize the potential to avoid the crash.

Kruszyna and Rychlewski [17], using research taken in two Polish cities, described the influence of approaching tram on behavior of pedestrians in signalized crosswalks. Measurements were done by counting pedestrians at zebra crossings close to the PT stop, those waiting for green, crossing on red but without dangerous situations, and crossing on red with a risk of being hit by car. Presence of tram increases intensity of a red signal violations from 10 to 60% depending on the type of PT stop. It was also observed that pedestrians may provoke other pedestrians to cross on a red signal and that traffic control, which guarantees boarding to PT vehicle, is a very important factor to avoid risk behavior.

Granie et al. [18] found that pedestrians are significantly more inclined to take the decision about crossing the street in the city center than in the suburbs or

countryside. This should be taken into consideration on tram crossings.

Thakur and Biswas [19] made a wide overview on assessment of pedestrian – vehicle interaction on urban roads, including the influence of pedestrian movements on vehicular speed, road safety, and capacity. Conclusions are similar in relation to vehicle speed and crash severity but no correlation between speed and crash frequency was found.

Castanier et al. [20] examined how different road users assess the risk of tram crashes with themselves and with other road users. The results showed that pedestrians, cyclists, and motorists perceived the risk of a crash between a tram and themselves to be very low ($M = 1.53$ and $SD = 0.88$) and with other users to be higher ($M = 2.28$ and $SD = 1.06$); therefore, they expressed relative optimism. The results also revealed realistic optimism among pedestrians and unrealistic optimism among young motorists. Road users have unfortunately relatively weak awareness of crash risks with trams.

The role of speed management as a means of improving pedestrian safety was recognized in a study by Gaca and Kiec [8]. Authors of this work described a correlation between type of pedestrian crossing (infrastructure) and pedestrian safety based on vehicle speed. In general, it might be used to evaluate safety of pedestrians on tram track crossings. Such a safety can be described by the following formula:

$$RP_F = \sum_i rEi(S_i) \times P_i(S_{0i}), \quad (1)$$

where RP_F – risk of pedestrian fatalities, expressed as a probable number of pedestrian fatalities; $rEi(S_i)$ – risk exposure expressing the number of conflict situations between vehicles and pedestrians at a speed equal to S_i before the crossing; and $P_i(S_{0i})$ – pedestrian death probability when hit by a vehicle with an impact speed S_0 .

The model presented above might be used in practice to analyze a risk on tram level crossings in case of $P_i(S_{0i})$ function identification, that was one of the inspirations to find the impact speed factor.

The complete formula for function $rEi(S_i)$ is difficult to determine. If we assume an even distribution of occurrence probability of a vehicle-pedestrian conflict situation (intrusion), independent of speed, $rEi(S_i)$ can be estimated using the following equation:

$$rEi(S_i) = V \times f(S_i) \times P_{ped}, \quad (2)$$

where V – number of vehicles during the analysis period; $f(S_i)$ – value of the speed distribution for speed S_i (mid-range); and P_{ped} – probability of pedestrian intrusion.

The model can be used to compare different risks on tram crossings across pedestrian crossings at the same locations, depending on the tram speed distribution. Assuming that the P_{ped} functions in scenarios A and B are the same but differ in tram speeds, the probability coefficient of no road incidents – HR – can be analyzed. This includes situations where the impact speed is 0 km/h or the speed is relatively safe ($P < 0.05$). HR can be calculated using the following equation:

$$HR = \frac{F_{PA}}{F_{PB}}, \quad (3)$$

where F_{PA} and F_{PB} – values of the cumulative speed distribution at a given pedestrian fatality probability $P = 0$ or $P < 0.05$ for situations A and B on road, respectively.

The use of the described model requires prior determination of the form of the function $P_i(S_{0i})$ – pedestrian death probability when hit by a vehicle with an impact speed S_0 .

Comparison of the form of the function $P_i(S_{0i})$ for a car and a tram has an additional important meaning due to the implementation of traffic management means – it helps answer the question whether speed limits for cars and trams should be different.

Due to the abovementioned reasons, the next step of the study was to seek function $P_i(S_{0i})$ in a form comparable to the hitherto determined ones for cars [10,11].

3 Research on the influence of tram impact speed on fatality risk of pedestrian

3.1 Methods

It was decided to use the two largest databases in Poland recorded by the Warsaw Trams and Krakow Public Transport Operator (MPK) with the best in-depth accident descriptions. Police database do not record all necessary data, e.g., slight injury collisions and serious injury accidents are mostly not available as it is a prosecutor material.

PT operators databases in Poland are mostly general but there are a few exceptions like Warsaw and Krakow, where since c.a. last decade, detailed information including injury description and photos from the accident place was being recorded. In Warsaw and Krakow, on-board computers record tram traffic data. As a result, downloading from the on-board computer the data from the last minute of the

vehicle's operation before the accident enables a more detailed identification of the circumstances of the accident.

Two methods of impact speed identification are used: direct research on a vehicle computer download taken after the accident by the PT operator inspector or calculation based on the distance between the localization of the pedestrian hit (from accident description and photos) and the stop of the tram front.

It was assumed that the tram driver continues a constant emergency braking without any gaps after hitting a pedestrian. Such a behavior is confirmed by drivers' feedback. Their opinions are similar to the results of breaking distance analysis based on the on-board computers.

More than 400 accidents were analyzed (all since last year) from which 197 sample was possible to create. Part of the data could not be used in the analyses because it was not possible to identify the distance between the collision localization and the stop of tram front, and data from on-board computer was unavailable.

The analysis concerns fatal accidents caused by trams hitting pedestrians at designated zebra crossings. All the analyzed cases, especially those with some information gaps, were discussed with PT operator inspectors who mostly have remembered the circumstances of major part of the accidents. Their knowledge was used for methodological verification of results. Logistic regression analysis was applied to the sample in order to identify correlation between the impact speed and pedestrian fatality risk.

Each accident in the sampled data was categorized as either non-fatal or fatal. The logistic model used is:

$$P(\text{non-fatal accident}) = \pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}}, \quad (4)$$

and thus,

$$\begin{aligned} P(\text{fatal accident}) &= 1 - P(\text{non-fatal accident}) \\ &= 1 - \pi(x) = \frac{1}{1 + e^{g(x)}}, \end{aligned} \quad (5)$$

where $g(x)$ stands for the function of the independent variables:

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n. \quad (6)$$

In the analyses, it was assumed that due to the purpose of the research and the limited data set, only impact speed will be the explanatory variable. Under this assumption, the logistic model has the form:

$$P(V) = \frac{1}{1 + e^{(a+bV)}}, \quad (7)$$

where V is the impact speed and a and b are two parameters to be estimated by the method of maximum likelihood, same as in the method by Brooks-Bartlett [21].

The P -value for the residuals, likelihood ratio tests, and analysis of deviance were used to assess the compliance of the estimated function with empirical data [22].

The "odds ratio" (OR) values were also estimated. The OR is a statistic that quantifies the strength of the association between the two events, A and B. The OR is defined as the ratio of the odds of A in the presence of B and the odds of A in the absence of B, or equivalently (due to symmetry), the ratio of the odds of B in the presence of A and the odds of B in the absence of A. Two events are independent if and only if the OR equals 1, i.e., the odds of one event are the same in either the presence or absence of the other event. If the OR is greater than 1, then A and B are associated (correlated) in the sense that, compared to the absence of B, the presence of B raises the odds of A, and symmetrically the presence of A raises the odds of B. Conversely, if the OR is less than 1, then A and B are negatively correlated, and the presence of one event reduces the odds of the other event.

3.2 Results

In order to estimate the parameters of the function (7) describing the relationship between impact speed and pedestrian fatality risk, the data regarding 197 registered and precisely identified accidents of tram hitting a pedestrian were used. One of the elements of identification was the speed of the tram hitting a pedestrian. Table 1 shows the number of fatalities due to hitting the pedestrians in various speed ranges recorded in the study.

Based on the above data and assuming the general form of the function described by equation (7), the fatality risk function was determined with the following equation:

$$P(V) = \frac{1}{1 + e^{(2.84791 - 0.079136V)}}. \quad (8)$$

The model parameters estimation are as follows:

Parameter	Estimate	Standard error
Intercept	2.84791	0.472587
V	0.079136	0.016849

Table 1: Distribution of the fatal accidents

Tram impact speed (km/h)	Cases	Fatal accident
1–9	20	2
10–19	53	7
20–29	71	21
30–39	36	21
40–49	15	5
50–59	2	2

Figure 2 shows pedestrian fatality risk as a function of the impact speed (km/h) when hit by the front of tram. Red curves show a 95% confidence limits.

The speed factor contributing pedestrian fatality is measured by “OR,” in this case equal to 1.082 (95.0% confidence intervals for ORs: 1,047–1,119), which indicates that the concerned factor leads to higher risk of fatality (with $P < 0.05$).

There is a statistically significant relationship between the variables at the 95.0% confidence level. In addition, the P -value for the residuals is 0.1815, indicating that the model is not significantly worse than the best possible model for this data at the 95.0% or higher confidence level. The percentage of deviance in fatal explained by the model is equal to 10.88%. This statistic is similar to the usual R -squared statistic. The adjusted percentage, which is more suitable to compare models with different numbers of independent variables, is equal to 9.2%.

Figure 2: The fatality risk as a function of impact speed for pedestrian hit by the front of a tram.

4 Discussion and case study

4.1 Discussion

The model (8) shows a significant difference in impact speed and risk of a fatal accident with pedestrian when one compares car and tram cases (Table 2).

It clearly shows that there is a much higher probability of death when pedestrian is hit by a tram with a speed of 30 km/h (almost 40%, in relation to 5% when hit by car). There are even cases of deaths with a very low speed of tram (5–10 km/h) which, according to detailed accident description, might be a result of the tram’s front shape and gaps, being a reason of getting a pedestrian under the tram.

Fatal risk for pedestrian hit by tram with impact speed of 50 km/h is two and a half times higher (75%) than in the case of car (30%).

This situation might be a result of:

- Ergonomics of the vehicles front which in case of trams cause full transmission of the energy to the weak human body;
- Further injuries due to the infrastructure (tracks, stones, etc.).

Additionally, it should be noted that changes in the old tram front structures may contribute to reducing the severity of the accidents with pedestrians [12]. In the presented research, it was possible to identify 121 incidents from 197 incidents according to the vehicle type – whether it was low floor modern or high floor old tram with high front. The modern tram appeared in almost 59% cases of trams involved in crash. 31% out of 61

Table 2: Comparison of the pedestrian fatality risk when being hit by a car and tram

Impact speed (km/h)	Fatality risk	
	Car ^a (%)	Tram (%)
20	2	22
30	5	38
40	14	58
50	30	75
60	55	87

^a Fatality risk value is determined using the “Overall estimate” curve in Figure 1.

incidents with seriously injured pedestrians is related to modern vehicles. The relation between the vehicle type and risk of fatal injury was not thoroughly analyzed at this stage of research. Average share of modern tram vehicles among the fleet during the data collection time was between 30 and 40%. However, it needs to be noted that the results of the analysis of the impact speed influence on fatal risk for pedestrians hit by tram, were compared with data collected for vehicles in a similar time-frame (vehicles with varying degrees of advancement in terms of pedestrian protection).

Some cities in Poland are rapidly changing trams for more modern and user-friendly vehicles. The construction of tram tracks in zones with pedestrian traffic is also changing, being often sheltered so that they do not cause secondary injuries to people hit by trams and falling onto the tracks. These two factors should lead to decrease in pedestrian fatality risk when being hit by a tram [12]. This means that the use of the relationship (8) in design practice and in speed management will require an update in the commencing years (re-determination of the equation coefficients).

4.2 GPS tram speed as measure of pedestrian risk

As a rule, trams are equipped with GPS devices that enable the registration and recording of speed data in connection with the location of the tram. Based on these data, it is possible to estimate with high accuracy the speed of a tram hitting a pedestrian. This speed can be calculated by assuming the deceleration characteristic for each type of vehicle. The moment of starting the braking manoeuvre depends on the visibility conditions of the conflict site (intersection of the tram track with the pedestrian road) and on the moment the pedestrian enters the conflict zone. The latter condition is a random variable. However, it can be assumed that there are factors favoring the incorrect behavior of pedestrians and their entering the crossing described as “intrusion.” There

are insufficient data to generalize a quantitative description of such pedestrian behavior, but based on the observations at specific sites, such sites can be classified, at least qualitatively, as “relatively safe” or “at risk.” In places defined as “endangered,” the speed of the tram can most likely be close to the speed of impact. Thus, it can be used as an indirect measure of the risk of accidents.

Based on the knowledge of the tram speed before reaching the conflict zone, the speed can be managed so that, if necessary, it is possible to reduce the tram speed to a relatively safe level. The fact that the assumption presented above is reliable can be shown by the comparison of registered data on speed and accidents with pedestrians as follows below.

To confirm the model in practice, data considering tram speed at different localizations have been downloaded from TTSS system in Krakow (ITS managing tram system) to find a correlation for sites where fatal accidents occur. At all three chosen localizations, where pedestrians were fatally hit by the tram, speed indicators were significantly higher, compared to the one (Grzegorzeckie Roundabout) at the same corridor, with similar number of red light violations (Table 3).

4.3 Wroclaw case study

Using the described considerations on the potential link between the tram speed and the risk of accidents involving pedestrians, an analysis of road safety risks was carried out in a real scenario (real testing ground).

A research for a large public transport node was taken in Wroclaw, where the Municipality was analyzing the possibilities to change the pedestrian paths between PT platforms and the hub exits from existing underpasses for level crossings with signalization (Figure 3). The research gave positive results in time saving, but the question about safety conditions, including potential risk of serious accident, becomes strong.

The trams’ speed and the traffic volume were measured as safety indicators. The probability of pedestrians

Table 3: Tram speed at different locations (bold without fatal accident)

Site	Average speed V_{av} (km/h)	Max. speed V_{max} (km/h)	Standard deviation S_d (km/h)	Median (km/h)	Test
Szwedzka	28.3	46	5	28.3	1,121
Kielecka	41	56.67	8	42.3	779
Hala Targowa	19.6	34.7	5	19.7	908
R. Grzegorzeckie	14.3	37.6	4.3	12.7	910

Figure 3: Routes of entering trams to the platforms and localization of level crossings (A, B, and C).

crossing the red light was estimated at 30–60%, which is a high level. Since risk is a function of the probability of pedestrian error (red signal input) and the consequences of this error, the impact speed can be used as a second variable to estimate the risk level for each crossing.

Each level crossing (A, B, and C) was observed in the scope of the tram speed using a hidden speed radar (Table 4). Three out of five routes had an average speed of entering trams at minimum level of 30 km/h. According to the impact speed diagram, there is an almost doubled risk of fatal accident (38%) when tram hits the pedestrian with 30 km/h speed, compared to the speed of 20 km/h (22%) (Table 2).

Research results confirmed a need to create a level crossing path for pedestrians, but only in the case of implementation of corrective actions, which are changes in signalization plan and introduction of the speed limit of maximum 20 km/h for trams entering platform and crossings area, independent of the existing speed limits. The risk is still visible with such speed, but it is not higher than in the case without changes in infrastructure. Speed limits are necessary despite the use of traffic lights, as observations have shown that 30–60% of the pedestrians cross during the red light. It was found that the change in the tram speed does not reduce the capacity of the transport node, as vehicles mostly use less time to evacuate than it is allowed by the traffic signalization.

5 Summary

Results of the analysis brought conclusions that planning of the urban street infrastructure needs to focus more on the risk assumptions for VRU. Tempo-30 zones are mostly

Table 4: Average tram speed when entering a level crossing on transport node

Route	V (km/h)	V (m/s)	Quartile 3 (km/h)
1A	29	8.1	30
1B	22	6.0	25
2A	21	5.9	22
2B	24	6.6	30
C	29	8.0	30

safe when one considers typical cars, but in the case of streets with light rail network, when a collision between a PT vehicle and pedestrian occurs, an impact speed might reach even 25 km/h. In this case, one out of three incidents will end up with a fatal victim. Therefore, trams should not travel more than 20 km/h in such zones. It is also recommended to formally verify and distinguish the “residential areas” where pedestrians have priority, and the “shared spaces” where none of the street users has it. Due to the fact that spaces with a speed limit of 20 km/h and with absolute priority for pedestrians in tram corridors reveal a 10 times greater risk of a fatal accident than in a “car-pedestrian” collision, and hence priority should not be given to pedestrians in zones with trams.

All tram or light rail stops with existing level crossings should be organized to disable high speed of PT vehicles. It especially concerns planning the traffic priority at intersections, which enable entry of the tram with high speed, as well as designing platforms’ length which changes the stop line of the vehicle and extends the braking, and, in consequence, also brings higher speed of the PT vehicles in the area of zebra crossing located mostly at the beginning of the platform.

Impact speed indicator for light rail should be used for research on public transport stops’ safety and urban street infrastructure design. Aiming at this, the HR described in the article by the formula (3) can be used.

The analysis has confirmed the high usefulness of the speed data recorded as part of the tram operation monitoring to assess the risk level in conflict zones with pedestrian traffic. The usefulness of this data depends on the extent of the sampling rate. It should enable an accurate mapping of speed profiles in conflict zones.

The presented results are burned by several limitations and therefore it is necessary to continue research aimed at the following issues:

- determination of a tram hitting the pedestrians effects at the most common speeds of 20–30 km/h (and various ages of pedestrians);

- assessment of the modern trams front shape impact on the reduction in the consequences of hitting the pedestrians;
- development of the CMF factor for crashes involving pedestrians in conflict zones with trams for various pedestrian crossings and tram speed limits.

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