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# THE INFLUENCE OF THE CONSTRUCTION OF TRAM FRONTS ON THE CONSEQUENCES OF ACCIDENTS WITH PASSENGER CARS

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Abstract. In recent years, there has been a large increase in passenger and public transport in cities. An increase in traffic flow results in an increasing risk of accidents. Manufacturers and operators of trams are increasingly subject to higher requirements for ensuring the safety of vehicles. Vehicle safety can be divided into two groups: active and passive safety. Systems and elements of active safety are intended to reduce the risk of accidents. Systems and elements of passive safety are intended to minimize the consequences of accidents. The requirements for the passive safety of newly designed railway vehicles are described in standard EN 15227. Standard EN 15227 was created due to the effort to protect passengers and crew inside railway vehicles in the event of an accident, so it is a so-called self-protection. The standard EN 15227 does not stipulate any requirements for so-called partner protection. Partner protection means an approach in which the vehicle protects passengers inside and outside the vehicle with its deformation elements.

This article deals with the issue of how the construction of the front of tram vehicles designed according to the requirements of the standard EN 15227 will affect the consequences of tram´s accidents with passenger cars. The first part of the article describes the requirements of the standard EN 15227 for newly designed trams. Than it describes the creation and evaluation of tram accident statistics in the Czech Republic for the years 2016 to 2018 with regard to the types of collision vehicles, collision directions and consequences of accidents. From the results of the evaluation of the accident statistics, a collision scenario was determined, in which the passengers inside cars were most often injured. The last part of the article is devoted to the creation of simulation models of accidents of three trams with a car and evaluation of simulation calculations with regard to the risk of injury to car´s driver in an accident with trams using human biomechanical criteria.

Keywords: Tram, cars, vehicle safety, passive safety, accident, EN 15227, human biomechanical criteria.

## 1. Introduction

The modern tram transport, today provided mainly by partially or fully low-floor vehicles, belongs to one of the basic pillars of the public transport in every modern city with a population over 100 000 inhabitants. The tram transport is most often used to transport large numbers of passengers from more remote neighbourhoods to the city centre. Due to the historical development of most European cities, it is not possible to operate trams on their own transport lanes separated from other road users and thus completely eliminate the risk of accidents. Due to the need to change the direction of the travel, tram tracks cross with the lanes of other road users. Each of these crossings increases the risk of a tram accident with passenger cars (hereinafter only cars).

Every tram accident with another road user is a major intervention in the flow of the passenger transport. The accident will result in a temporary local paralysis of the tram system, as the vehicles must remain at the scene of the accident until the accident is recorded by the staff of transport company and is given a permission to clear the accident from the Railway inspection. It takes an average of 20 minutes to clear accidents with a material damage. With more serious consequences, such as a serious injury or a death, it takes 2 to 3 hours to clear accidents. The entire section of the tram line is impassable during the entire period of clearing the consequences of the accident, which leads to delays of other trams and displeasure of tram users.

Traffic accidents are most often caused by human faults. Unfortunately, in the road transport, the highest price is often paid for these faults, namely the health or the life of the accident participants. The vehicle design must therefore be carried out with the knowledge that people are making mistakes and, despite the introduction of the improved active safety features, accidents cannot be prevented with an absolute certainty. Therefore, it is necessary to equip newly designed vehicles with improved elements of passive safety, which will lead to reducing of the consequences of accidents on all vehicles involved in the

Figure 1. Tram ŠKODA 15T Praha [2].

Figure 2. Tram ŠKODA 39T Ostrava [3].

accident. This vision of an approach to increase road safety and reduce the consequences of accidents on passenger health is based on the Vision 0 program, which was introduced in 1995 in Sweden. The basic goal of the Vision 0 program is to create and adopt such measures of the transport system and on vehicles in order to prevent deaths and to minimize serious injuries caused by traffic accidents by 2050 [1].

To increase the passive safety of newly designed railway vehicles, the standard EN 15227 was issued in 2008. At present, trams of older production times are operated in the Czech Republic. These trams were not designed in accordance with the requirements of standard EN 15227. Examples of older trams are T3, ŠKODA 14T and 15T (see Figure 1). In recent years, the vehicle fleet in the Czech Republic is being renewed. For example, the new trams from ŠKODA, which are in operation in Ostrava (see Figure 2), Pilsen and will soon be in operation in Brno. These new trams are already designed according to the requirements of the EN 15227 standard for protection during accidence.

This article deals with the assessment of how the construction of tram fronts according to the requirements of the standard EN 15227 will affect the consequences of an accident on cars. The research compares three low-floor trams, which are operated in the Czech Republic. The research mentioned in the article is a part of the research of the proposed modification of tram fronts to reduce the consequences of accidents on passenger cars, which is carried out at the Faculty of Mechanical Engineering, CTU in Prague.

## 2. Standard EN 15227

The first revision of standard EN 15227 was issued in 2008 due to the large number of accidents involving railway vehicles and the high number of injured passengers inside railway vehicles caused by accidents. A second revision of the standard was issued in 2020 supplemented by new knowledge from operation of railway vehicles, which were designed according to the previous version [4].

The main objective of EN 15227 is to reduce the consequences of railway vehicles accidents and to ensure the safety of passengers and crew inside railway vehicles in the event of an accident. It is therefore a so-called self-protection approach, where the vehicle protects only the occupants inside the vehicle and takes other road users aa collision barriers. The requirements of the standard are most often demonstrated by numerical simulation on models that are validated according to impact tests of crash parts of railway vehicles [4].

The standard EN 15227 divides railway vehicles into four design categories of the impact resistance according to the different type of the operation, in which the railway vehicle is operated. The construction categories of railway vehicles are listed in Table 1. Tram vehicles belong to the construction category C-IV [4].

Standard EN 15227 defines for each design category the collision scenarios for which a new railway vehicle have to be designed. The parameters of the individual collision scenarios were determined so that the collision scenarios as accurately as possible represent the accidents in which the given railway vehicle is most often involved in operation. The following collision scenarios are defined for tram vehicles: a head-on collision of two identical trams, a collision of a tram into a rigid obstacle weighing 3 tonnes and a collision of a tram into deformable obstacle weighing 7.5 tonnes [4].

### 2.1. The collision scenario: the frontal impact of two identical trams

This collision scenario represents a head-on accident with two trams. Frontal accidents of two trams are not so common, but they place the greatest demands on the absorbed energy by the deformation elements and the functionality of anti-climbing devices. Accidents involving the climbing of one tram on another usually result in the highest number of injuries of passengers, and therefore the risk of a tram climbing in an accident must be minimized. The consequences of an

| Category | Definition | Examples of vehicle types |
|---|---|---|
| C-I | Vehicles intended for operation on trans-European network, international, national and regional lines | Locomotives, passenger cars |
| C-II | Urban vehicles intended for operation only on dedicated railway infrastructure without a link to road transport | Subway vehicles |
| C-III | Light railway vehicles intended for operation in urban or regional networks, in operation on shared lines and linked to road transport | Suburban tram |
| C-IV | Light railway vehicles intended for operation on dedicated urban networks with a link to road traffic | Tram vehicles |

TABLE 1. Railway vehicles design categories according to the standard EN 15227 [4].

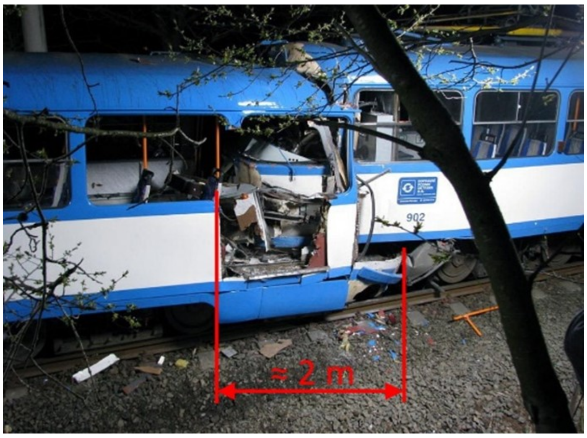



FIGURE 3. An accident of two trams type ČKD T3, during which the tram climbed [5].

FIGURE 4. An accident of two trams type Stadler Tango NF2 with anti-climbing protection [6].

accident of this type are shown in Figure 3. In the accident of two T3 trams, one tram collided with another within a distance of approximately 2 meters, resulting in the deaths of 3 passengers. Figure 4 shows the consequences of a head-on accident involving trams equipped with an anti-climbing device [4].

The collision scenario is defined as follows: the first tram stands unbraked on a straight track. The second tram starts on a straight track at a speed of $15\,\mathrm{km\,h^{-1}}$. The second tram hits the first tram from behind [4].

FIGURE 5. An accident of the tram ŠKODA 15T with a car [7].

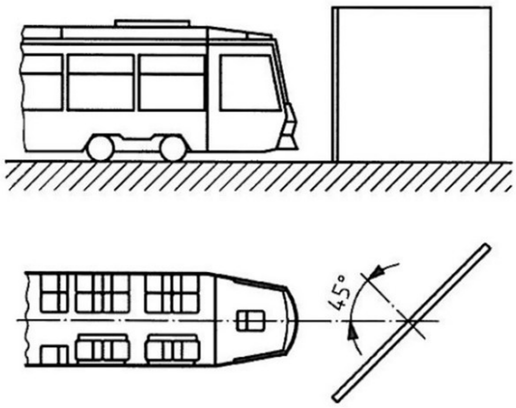



FIGURE 6. The scheme of the collision scenario of a tram and a rigid obstacle [4].

### 2.2. The collision scenario: a tram crashes into a rigid obstacle weighing 3 tonnes

This collision scenario represents a tram accident with a car or a small truck (see Figure 5). Trams and cars accidents most often occur at a crossing of a tram line with a road. The scheme of the second collision scenario is shown in Figure 6 [4].

The collision scenario is defined as follows: a rigid obstacle stands at an angle of 45° across the entire width of the tram. The tram starts on a straight track at a speed of $25\,\mathrm{km\,h^{-1}}$ and then collides head-on with a rigid obstacle. In the accident, the obstacle

Figure 7. Consequences of an accident between a T3 tram and a truck [8].

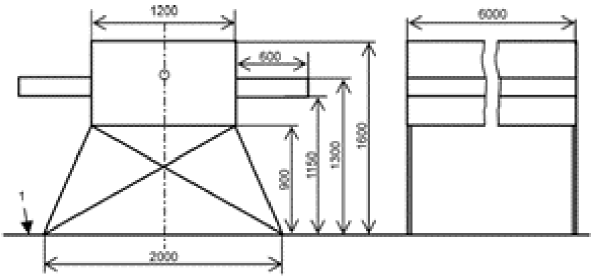



Figure 8. The scheme of the deformable obstacle [4].

may move in the X and Y axis, but it is not allowed to rotate [4].

### 2.3. The collision scenario: a tram crashes into a deformable obstacle weighing 7.5 tonnes

This scenario represents an accident between a tram and a truck or bus at a crossing of a tram line with a road. In tram-truck or bus accident, the point of contact between the vehicles in the accident is at the height of the tram driver's counter, often resulting in the destruction of the cab (see Figure 7). The geometry of the obstacle penalises this fact (see Figure 8) [4].

The crash scenario is defined as follows: the obstacle is perpendicular to the tram track at a speed of $15\,\mathrm{km\,h^{-1}}$ and then collides head-on into a deformable obstacle [4].

### 2.4. Conclusion

Trams constructed according to EN 15227 are designed to withstand frontal and frontal-side impacts with another vehicle. It can therefore be assumed that in these types of accidents between a tram and a car, only the energy absorbing elements will be damaged and no injuries to tram's passengers and driver will occur.

In order to filling the passive safety requirements of EN 15227, newly designed trams are equipped with energy absorbing elements and bumpers on the front and rear of the vehicle and a more robust rough structure design (see Figures 9 and 10).

Figure 9. The front of the tram ŠKODA 39T Ostrava [9].

Figure 10. The front of the tram Stadler Tango NF2 [10].

## 3. Accident statistics of tram vehicles in the Czech Republic

In order to verify the requirements of EN 15227 and to determine the most risky collision direction from the point of view of injuries to car occupant, statistics of accidents between trams and other road users in the Czech Republic for the years 2016 and 2018 were compiled. In compiling accident statistics, the cooperation was established with transport companies operating trams in the Czech Republic (see Table 2) and with the Police of the Czech Republic. Different institutions record different information about accidents and therefore it was necessary to link the databases to create comprehensive accident statistics. Transport companies record this data about accidents: date of the accident, location of accident, information about the vehicles, short description of the accident and material damage. Information on the health consequences of accidents for car occupants is recorded by the Czech Transport Police [11].

The total of 6 816 tram accidents with other road users was recorded in the Czech Republic from 2016 to 2018. Table 3 shows the number of tram accidents recorded by individual transport companies [11].

In order to be able to analyse accident statistics, a methodology was developed within the work on

| Transport company | Abbreviation |
|---|---|
| Transport company of the city Brno a.s. | DPMB |
| Transport company of the cities Liberec and Jablonec nad Nisou a.s. | DPMLJ |
| Transport company of the cities Most and Litvínov a.s. | DPMOST |
| Transport company of the city Olomouc a.s. | DPMO |
| Transport company of the city Ostrava a.s. | DPO |
| Transport company of the city Prague a.s. | DPP |
| Pilsen city transport companies a.s. | PMDP |

Table 2. Transport companies operating trams in the Czech Republic.

| Transport company | 2016 | 2017 | 2018 |
|---|---|---|---|
| DPMB | 423 | 453 | 412 |
| DPMLJ | 40 | 43 | 36 |
| DPMOST | 12 | 6 | 9 |
| DPMO | 46 | 35 | 46 |
| DPO | 154 | 199 | 180 |
| DPP | 1 294 | 1 566 | 1 547 |
| PMDP | 97 | 98 | 120 |
| **Total** | **2 066** | **2 400** | **2 350** |

Table 3. Numbers of accidents recorded by individual transport companies.

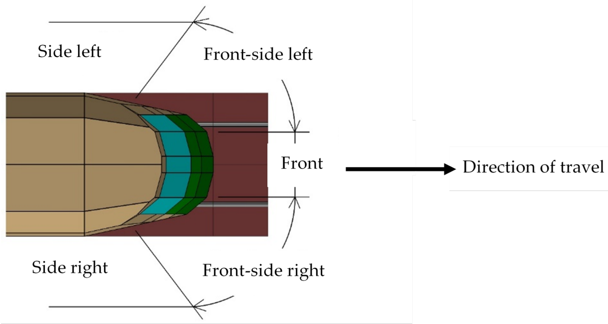



Figure 11. The evaluation criterion: the collision direction.

the project TN01000026, which evaluates individual accidents according to the following evaluation criteria: a type of a collision vehicle (a tram, a car, a truck, a bus, a motorcycle, a bicycle or a pedestrian), a collision direction (front, front-side left/right, side left/right or rear, directions were evaluated against the tram, see Figure 11), the culprit of the accident (a tram driver or a collision vehicle driver) and the consequences for the health of the occupants in the collision vehicle (an accident without consequences, a minor/severe injury or a death) [11].

To verify the requirements for the passive safety (the self-protection) of trams defined in the standard EN 15227, the accident statistics were evaluated according to the collision vehicle and the collision direction. The results of the evaluation are shown in Table 4 [11].

From the results shown in Table 4 it is evident that the scenario of a tram colliding with a rigid obstacle of 3 tonnes defined in EN 15227 is correctly selected, as this is the most frequent type of accident involving trams in service. There were 122 frontal accidents involving two trams during the period under evaluation. There were 104 head-on accidents between trams with a trucks and a bus during the evaluation period. It is therefore evident that the passive safety requirements for trams in EN 15227 are correctly defined and are based on accidents in which are trams frequently involved during normal operation [11].

The number of side accidents between trams and other road users is high. This type of accident is most often caused by a failure to estimate the clearance between vehicles. The consequences of this type of accident are most often only material damage [11].

Due to the conformity of the results of the accident statistics and the requirements of EN 15227 for newly designed trams, it can be assumed that in the case of an accident between a tram and a passenger car, there will be no serious damage to the tram and no serious injuries to the passengers inside the tram. Next, the research looked at the consequences of accidents on passengers in cars.

The evaluation of accident statistics showed that during the period from 2016 to 2018, most accidents were between trams and cars (the total of 5 046 accidents of this type). On average, there were more than 4 tram accidents with a car per day in Czech Republic.

The most common type of tram accidents with cars were front-side accidents from the right side (the total of 1 838 accidents). The higher frequency of accidents from the right side compared to the left side is due to the distribution of roads in the cities of the Czech Republic. The tram line is in the middle of the street and the roads for road vehicles are on the sides, see Figure 12 [12].

To determine the need for the research to increase the partner protection of trams in the event of an accident with passenger cars, accident statistics was evaluated according to the consequences on the health of passengers in cars. The results of the evaluation are shown in Table 5.

The evaluation of the accident statistics showed that 299 minor and 12 serious injuries to car drivers occurred in collisions between cars and trams during the period under study. The highest number of injuries to car drivers occurred in front and front-side crashes. Injuries occurred in one in seven front and one in

| Collision direction | | Collision vehicle | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | bus | pedestrian | bicycle | motorcycle | truck | car | tram |
| Front | – | 9 | 89 | 6 | 4 | 95 | 859 | 122 |
| Front-side | right | 18 | 162 | 3 | 7 | 277 | 1 838 | 1 |
| Front-side | left | 10 | 54 | 2 | 3 | 49 | 339 | 6 |
| Side | right | 71 | 95 | 4 | 9 | 451 | 1 754 | 11 |
| Side | left | 46 | 20 | 2 | 1 | 72 | 228 | 23 |
| Rear | – | 5 | 2 | 0 | 3 | 2 | 28 | 36 |
| **Total** | | **159** | **422** | **17** | **27** | **946** | **5 046** | **199** |

Table 4. The evaluation of tram accident statistics by the collision vehicle and the collision direction [11].

| Collision direction | | Total number of accidents [-] | Number of minor injuries [-] | Number of minor injuries [%] | Number of serious injuries [-] | Number of serious injuries [%] |
|---|---|---|---|---|---|---|
| Front | – | 859 | 141 | 16.4 | 9 | 1.0 |
| Front-side | right | 1 838 | 128 | 7.02 | 2 | 0.1 |
| Front-side | left | 339 | 21 | 6.2 | 0 | 0.0 |
| Side | right | 1 754 | 7 | 0.4 | 0 | 0.0 |
| Side | left | 228 | 1 | 0.4 | 1 | 0.4 |
| Rear | – | 28 | 1 | 3.6 | 0 | 0.0 |
| **Total** | | **5 046** | **299** | **5.9** | **12** | **0.2** |

Table 5. The evaluation of tram accident statistics according to the consequences on the health of passengers in cars.

Figure 12. The distribution of a communication in cities in the Czech Republic [12].


Figure 13. Consequences of a frontal tram collision into the side of a car [13].

seventeen frontal-side crashes. These crashes are most often caused by car drivers who fail to give the right-of-way to a parallel or oncoming tram when crossing the tram line. Due to the long braking distance, tram drivers no longer have time to brake the tram and consequently the tram's front end hits the side of the car. Due to the higher stiffness of the tram head, the sides of the passenger cars are more likely to be destroyed in an accident, resulting in a higher risk of injury to the car drivers. Figure 13 shows the consequences of a frontal crash of a T3 tram into the side of a car. The driver of the car was severely injured in the accident [13].

The results of the evaluation of accident statistics showed that the risk of an injury to the car crew in tram accidents is high. This conclusion confirmed the need for further research of reducing the consequences of tram accidents on cars. The highest risk of an injury is in frontal tram accidents with the side of cars, so further research will be conducted on these types of accidents.

During the period 2016 to 2018 were operated in Czech Republic only Stadler Tango NF2 trams, which were constructed according to the requirements of EN 15227. The first 2 units of the newly constructed trams were operated in Ostrava from October 2018. By the end of 2018, a total of 26 units of these trams were put into operation [14]. In the last three months

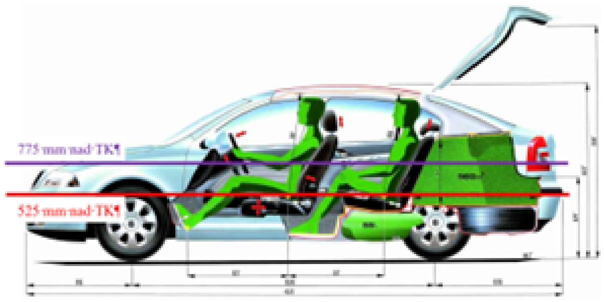



FIGURE 14. Contact points for different bumper heights.

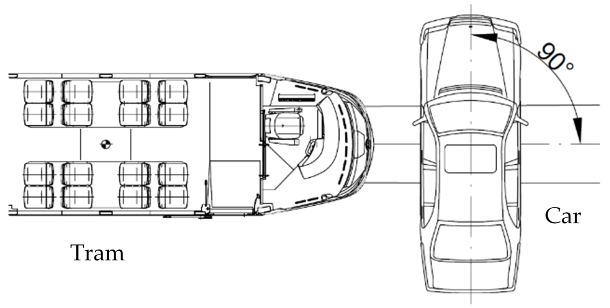



FIGURE 15. The scheme of the proposed crash scenario.

of 2018, the new trams were involved in 2 frontal and 2 side accidents with cars. One frontal accident caused serious injuries to the car's driver and the other one did not result in any injury. Due to the small number of accidents it was not possible to assess the effect of the tram's front design according to the requirements of EN 15227 on the consequences of accidents with cars from the evaluation of accident statistics. Therefore, further research was carried out using the simulation software LS-Dyna.

## 4. Selected trams for research

The newest trams operated in the Czech Republic with different front construction were chosen for the research. For the purpose of the research, the selected trams were generally named as type A, B and C.

The trams type A are operated on the territory of the city Prague since 2011. Currently, DPP operates 250 of these trams [15]. The tram type A was chosen because of the absence of a bumper on the front of the tram. In the event of an accident between a tram and a car, the tram front lining and the anticlimbing device come into contact with the side of the cars (see Figure 5).

The trams type B are among the most modern trams operated in the Czech Republic. The first trams were delivered to the DPO at the end of 2021. A total of 35 trams are to be delivered to the DPO [3]. The tram type B was chosen due to the location of the energy absorber axes at a height of 775 mm above the TOR (see Figure 14). The contact points of the tram bumper with the side of the car are at the height of the passenger's chest in car.

The first trams type C were delivered to the DPO at the end of 2018. Currently, the DPO operates 40 of these trams [14]. The tram type C was chosen due to the location of the energy absorber axes at a height of 525 mm above the TOR (see Figure 14). The contact points of the tram bumper with the side of the car are at the height of the passenger's pelvis in car.

## 5. Design of crash scenario

According to the results of the evaluation of the accident statistics presented in Table 5, the most frequent injury to car's drivers occurs when a tram crashes frontal into the side of a car. The crash scenario for the research was designed to represent a tram hitting the side of a car at the driver's door. The collision scenario was designed as follows: a car stands perpendicular across the tram lines, the tram starts moving and collides head-on into the side of the car. The car can move in all directions. A scheme of the proposed collision scenario is show in Figure 15.

The speed of the tram before the accident is an important factor that influences the consequences of accidents. When the accident statistics were compiled, this data was not provided by the transport companies for individual accidents and therefore it was not possible to determine the average tram speed at the time of the accident. For this reason, the following tram speed at impact were chosen for the research: 10, 15, 20, 25, 30, 40 a 50 $\mathrm{km\,h^{-1}}$. The speed of 50 $\mathrm{km\,h^{-1}}$ is the maximum operating speed of trams in mixed traffic.

## 6. Creating a simulation model

The simulation models were created to represent as closely as possible the proposed scenario of a collision between a tram and a car. The simulation models were composed of submodels: tram, deformation element, car and driver. The simulation model of the accident between a tram type B and a car is shown in Figure 16. The parameters of each submodel will be described in the following chapters. The individual parts of the simulation models were created in the environment of Catia V5, Ansys and LS-PrePost.

### 6.1. The simulation models of trams

When constructing trams, their rough structures are dimensioned according to the legislative requirements for durability and strength in normal operation and in the event of an accident. Simulation models of trams are then created to represent the rough structures of real trams as closely as possible. The crash calculations performed on these models can predict with high accuracy the course of accidents and possible deformations of the rough structures of the car bodies. During the development of this research, it was not possible to obtain detailed drawings of individual trams in order to create accurate simulation models.

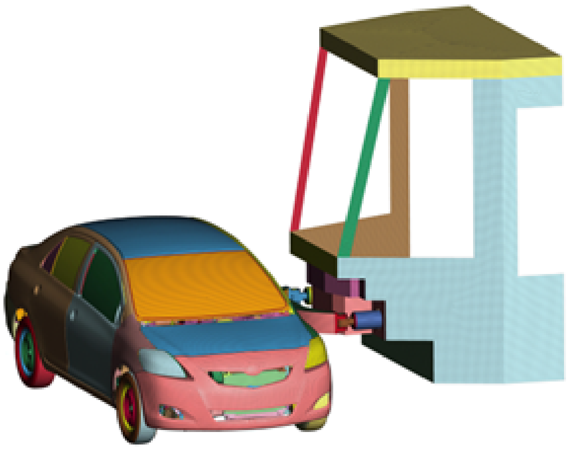
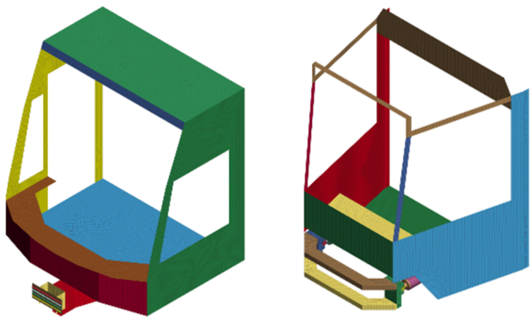


FIGURE 16. Simulation model of an accident between a tram type B and a car.



(A). (B).

FIGURE 17. Simulation models of trams, (A) – type A, (B) – type C.

Therefore, the 3D geometry of the tram simulation models was created from freely available documents and photos on the internet.

For the research, the assumption was made that due to the high strength of the rough structures of the tram car bodies, no plastic deformation will occur in the event of an accident with cars. According to this assumption, the tram models were considered as rigid in the calculations. This assumption resulted in a smaller error than if the tram models were considered as deformable and the calculation would have resulted in unrealistic tram deformation and smaller car deformation.

For this reason, the tram simulation models (see Figures 16 and 17) were represented only by tram's cabin, which were considered as perfectly rigid and the masses of the whole trams were defined for them (see Table 6). The remaining parts of the trams were not considered as a more complex model would lead to longer computational times of the simulations without any contribution to the accuracy of the results.

The formula for calculating the collision mass of a tram is defined in the standard EN 15227 (see Equation (1)) [4].

| Parameter | Type A | Type B | Type C |
|---|---|---|---|
| Mass of an empty tram [kg] | 43 790 | 36 835 | 34 500 |
| Number of seats [-] | 60 | 60 | 61 |
| Mass of a passenger [kg] | 70 | 70 | 70 |
| Collision mass of the tram [kg] | 45 890 | 38 935 | 36 670 |

TABLE 6. Mass parameters of trams [14, 16, 17].

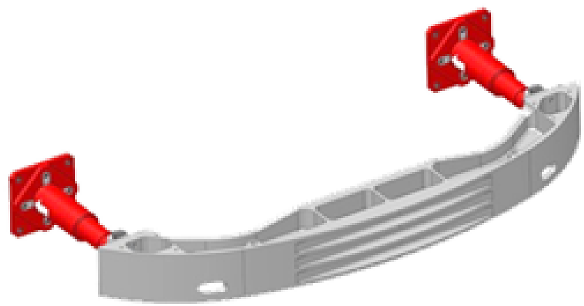


FIGURE 18. The example of the deformation element [18].

$$m_{col} = m + m_{pass} * \left(\frac{P_{seats}}{2}\right), \tag{1}$$

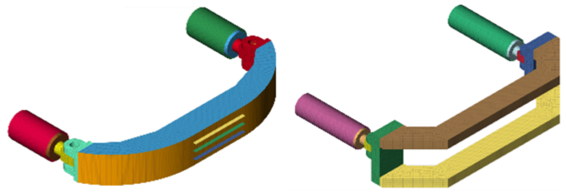
where: $m_{col}$ – collision mass of tram, $m$ – mass of empty tram, $m_{pass}$ – mass of passenger, $p_{seats}$ – number of seated passengers.

### 6.2. THE SIMULATION MODEL OF THE DEFORMATION ELEMENTS

Deformation elements of newly constructed trams most often consist of two absorption elements connected by a stiff bumper (see Figure 18). Absorption elements are able to absorb the energy of the impact. The requirement for the value of the absorbed energy is defined by the collision scenario of two trams at a speed of 15 km h$^{-1}$ in standard EN 15227 [4].

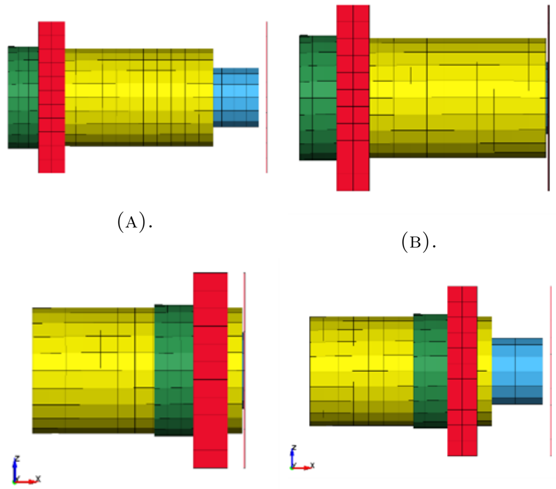
The simulation models of the deformation elements of trams type B and C were created to represent as accurately as possible the real deformation elements used on both trams. The models consisted of two absorber members to which the bumper was attached via a rotation joints (see Figure 19). Each absorber element was defined with a loading characteristic to absorb the required impact energy. The characteristics were determined according to the Oleo documentation and the requirements of EN 15227.

The functionality of the absorbers was verified by a calibration test in which the absorber member was compressed with the test fixture up to the overload area (see Figure 20). The test was used to evaluate the force dependence on the compression of the absorbing member. The test result was then compared



(a). (b).

Figure 19. Simulation model of the deformation element of the tram, (A) – type B, (B) – type C.



(a). (b). (c). (d).

Figure 20. The calibration test: (A) – before the test, (B) – compressing the return stroke, (C) – compressing the non-return stroke, (D) – after the relief.

with the designed characteristic (see Figure 21). The comparison achieved good fits and the models were evaluated as validated.

### 6.3. The simulation model of a passenger car

The parameters and the accuracy of the car's simulation model were critical for the research on reducing the consequences of trams and cars accidents. A poor and inaccurate car model would lead to poor results and inaccurate research conclusions. To create the detailed model of a car it would be necessary to know the design of the car and parameters of the used materials. To validate the model, it would then be necessary to perform impact tests and compare the test and simulation results. The creation of an accurate and validated simulation model of a car wasn't possible within this research project. Therefore, it was necessary to take over a model from another project.

The researchers at the National Crash Analysis Center (NCAC) at George Masone University (GWU) provide freely available simulation models of various road vehicles for crash simulations on their website (ccsa.gmu.edu). From the available models of road vehicles was chosen a model of the car Toyota Yaris 2010 (see Figure 22). Mass parameters of the simulation

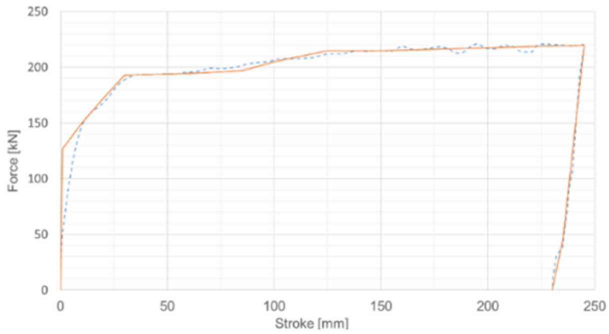



Figure 21. The characteristic of tram type B absorption element, orange line – design characteristics, blue line – validation test.

(a). (b).

Figure 22. (A) The car Toyota Yaris 2010 [19], (B) the simulation model of car Toyota Yaris 2010 [19].

model and the real car are listed in Table 7.

The simulation model of the Toyota Yaris 2010 car was validated according to several tests performed on a real vehicle (f.e. a frontal full wall crash, a frontal offset crash, a side impact NHTS, a side impact IIHS, etc., see Figure 23). For the research solution thus could be introduced the assumption that the results of simulation calculations performed on this model will correspond with high accuracy to the course of tests performed on a real vehicle.

### 6.4. The simulation model of the driver

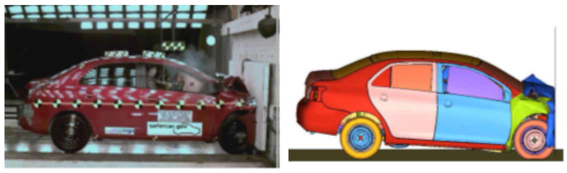
Human simulation models are created as copies of every mechanical dummy used in the crash tests of road vehicles. The reason is the best possible prediction of the consequences of various accidents on the passengers inside the vehicles already at the design stage of the vehicle. This procedure makes it possible to optimize the design of new cars even at the design stage, i.e. before a series production begins [21].

The most important parameter of human simulation models is a biofidelity. The biofidelity describes the similarity of the behaviour of the simulation model to the human body. With poor biofidelity, the result of simulations may lead to poor results and inaccurate research conclusions. The creation of such a model is highly demanding, requires precise knowledge of the behaviour of the human body under a mechanical loading and mass parameters of body parts. The creation of an accurate human simulation model wasn't possible within this research. Therefore, the human simulation model was taken from other project [21].

Livermore Software Technology (LSTC), manufac-

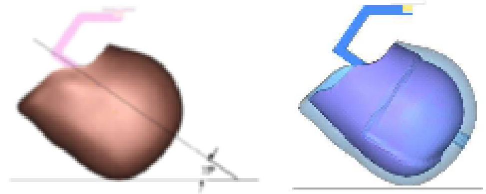
| Parameter | Unit | Real vehicle | FEM model |
|---|---|---|---|
| Mass | kg | 1 078 | 1 101 |
| Moment of inertia I_xx | $\mathrm{kg\,m^{-2}}$ | 388 | 395 |
| Moment of inertia I_yy | $\mathrm{kg\,m^{-2}}$ | 1 498 | 1 566 |
| Moment of inertia I_zz | $\mathrm{kg\,m^{-2}}$ | 1 647 | 1 739 |
| Position of COG x_t | mm | 1 022 | 1 004 |
| Position of COG y_t | mm | -8.3 | -4.4 |
| Position of COG z_t | mm | 588 | 569 |

Table 7. Mass parameters of the car Toyota Yaris 2010 [19].



(A). (B).

Figure 23. Front full wall crash test of Toyota Yaris 2010: (A) – real test [19], (B) – simulation [19].



(A). (B).

Figure 25. Frontal head drop test: (A) – actual test setup [20], (B) – FE simulation setup [20].

Figure 24. The simulation model WorldSID 50th Male [20].

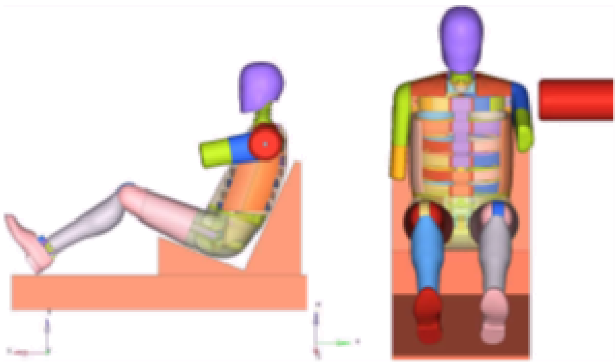


Figure 26. Shoulder test pendulum set up [20].

turer of Ansys software, provides validated frontal and side impact dummy models on its website (lstc.com). The proposed calculation scenario of the collision (described in Section 5) represents the frontal impact of the tram to the side of the car, i.e. the side impact to the car. From the available side impact dummies was chosen the WorldSID 50th Male dummy (see Figure 24). This dummy represents the average adult man weighing 74 kg [20].

The WorldSID 50th Male dummy model was validated according to the following tests: the two head drop tests (see Figure 25), the neck pendulum test, the shoulder impact test (see Figure 26), the thorax with and without impact test, the abdomen impact test and the pelvic impact test. The results of the simulation tests were compared with the requirements of the WorldSID ISO 15830-2 regulation. The results of the validation were in accordance with the requirements of the regulation [20]. For the research solution thus could be introduced the assumption that the results of simulation calculations performed on this model will correspond with high accuracy to the course of tests performed on a dummy.

The WorldSID 50th Male dummy model was created on the principle of rigid bodies. These types of simulation models are created from multiple rigid bodies, which are interconnected by bonds representing the joints of a person. To create such a model, it is necessary to know the dimensions of the human body, the mass properties of individual body parts (the position of the centre of gravity, the weight and moments of inertia), the positions of the joints and joints permissible ranges of motion. The advantage of these models is lower demands on a computing power and also easy positioning of the model. Calculations with the rigid body models are able to well predict human movement during and after an accident and acceleration courses acting on individual parts of the human body. The evaluation of the consequences of accidents will be possible by determining the acceleration courses of individual parts of the body from simulations and subsequent evaluation of human biomechanical criteria (see Section 6.5) [21].

### 6.5. Human biomechanical criteria

Human biomechanical criteria have been introduced to assess the effects of accidents on occupants inside road vehicles. Human biomechanical criteria define the relationships between physical variables and the probability of injury to occupants. In road motor vehicle approval tests, the measured values of the biomechanical criteria must be less than the specified limit values [21]. The acceleration of certain parts of the human body can be evaluated in simulations on the WorldSID 50th Male dummy model. From the biomechanical criteria used by Euro NCAP for the assessment of safety in side impacts. The following biomechanical criteria of the head were selected to assess the consequences of accidents: HIC15 and 3 ms [22].

#### 6.5.1. Human biomechanical criteria – HIC15

The HIC15 criterion evaluates the risk of injury from measured acceleration curves at the centre of gravity of the dummy's head. The value of the HIC15 criterion is determined from Equation (2) [23].

$$HIC = \left\{ (t_2 - t_1) \left[ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right\}, \quad (2)$$

where: $a$ – resultant acceleration in the multiples of the earth's gravitational acceleration $g$, calculation according to equation 3, $t_1$ – beginning of the observed event, $t_2$ – end of the observed event.

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2}\,. \quad (3)$$

According to the requirements of the Euro NCAP evaluation, the evaluation is performed in a time interval of 15 ms and sets two limit values of the criterion: a higher limit of 500 and a lower limit of 700. The higher the final value of the criterion is, the higher is the probability of injury to a person in an accident. New vehicle manufacturers strive to keep the value of criteria during an accident as low as possible. Therefore, the limit value of 500 was chosen for the research [22].

#### 6.5.2. Human biomechanical criteria – 3 ms

The biomechanical criterion of 3 ms is based on the WSTC curve (see Figure 27), which describes the relationship between the magnitude of acceleration and the duration of acceleration on the risk of permanent injury to occupants. According to the Euro NCAP assessment requirements, the acceleration of the driver's head for 3 ms must not be greater than 72 g (higher limit) or 80 g (lower limit). As with the HIC15 criterion, a higher value of the 3 ms criterion indicated a higher probability of occupant injury in a crash. Therefore, the 3 ms criterion limit value of 72 g was chosen for the research [23].

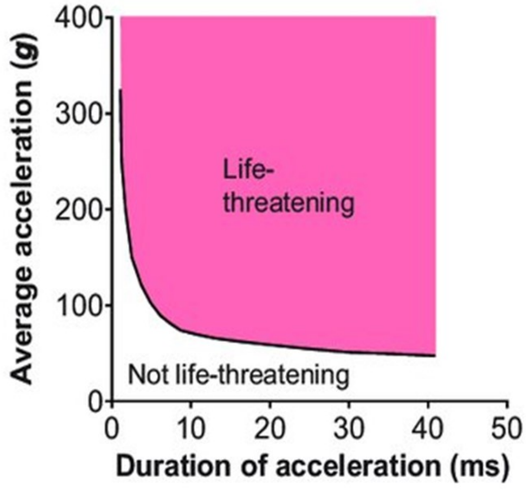



Figure 27. WSTC – Wayne State Tolerance Curve [24].

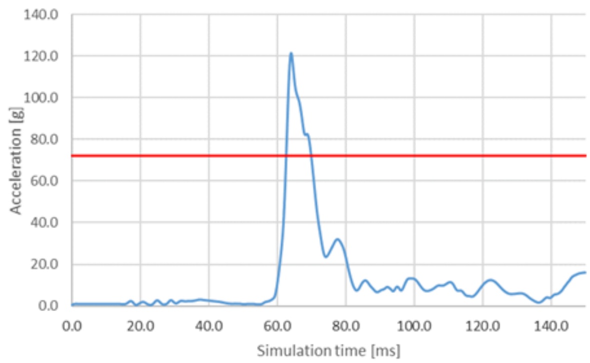



Figure 28. The acceleration of the driver's head during an impact of the tram type B at speed 25 km h$^{-1}$.

## 7. Results

Section 6 describes the creation of simulation models that represent the impact of the examined trams into the side of a car. Simulations performed on these models and the results of simulations are described in this chapter. The consequences of the accidents were evaluated according to the human biomechanical criteria described in Section 6.5 from the calculated course of the driver's head acceleration in the car.

Simulations of the impact of the trams type A, B and C into the side of the car were performed for the following impact speeds: 10, 15, 20, 25, 30, 40 and 50 km h$^{-1}$. The results of the acceleration of the driver's head for simulation of the impact of the tram type B at 25 km h$^{-1}$ are shown in Figure 28 and impact simulation process are shown in Figure 29. The results of the evaluation criteria for the individual trams and impact velocities tested are summarised in Tables 8 and 9.

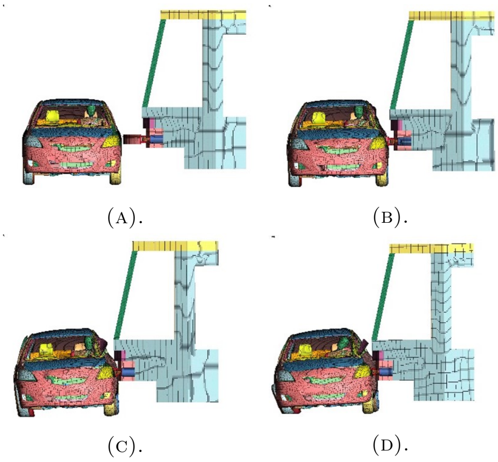


Figure 29. The impact of the tram into the side of a car at a speed of 25 km h$^{-1}$: (A) 0 ms, (B) 50 ms, (C) 75 ms, (D) 100 ms.

| **Speed of tram [km h$^{-1}$]** | **Type A [-]** | **Type B [-]** | **Type C [-]** |
|---|---|---|---|
| 10 | 25.7 | 44.6 | 39.6 |
| 15 | 73.7 | 157.0 | 122.9 |
| 20 | 165.8 | 348.7 | 266.0 |
| 25 | 335.5 | 671.2 | 593.9 |
| 30 | 478.0 | 911.3 | 852.9 |
| 40 | 783.3 | 1797.0 | 1720.0 |
| 50 | 1255.0 | 2177.0 | 2128.0 |

Table 8. The evaluation of the HIC criterion for individual impact velocities and trams.

## 8. Discussion

From the results of the calculations of the impact of a tram into the side of a passenger car shown in Tables 8 and 9 can be seen, that trams designed according to EN 15227 have a risk of severe injury or death to car occupants at impact speeds of 25 km h$^{-1}$ and above. For tram type A the limit values were exceeded at speed 30 km h$^{-1}$, even though tram type A has the highest collision mass and so the highest energy during the impact.

From the above conclusions tt can be concluded that the frontal design of the tram type B and C leads to a higher risk of injury to passengers inside cars than the tram type A. In order to meet the objectives of the Vision 0 program, i.e. to reduce the risk of serious injuries and the death of passengers in an accident, it is appropriate to supplement the requirements of EN 15227 with additional legislation that would lead to increase the safety of other road users during the accident with trams. The creation of a methodology describing the safety assessment of trams in the event of an accident with cars is one of the outputs of research SGS19/161/OHK2/3T/12, which is carried out at the Faculty of Mechanical Engineering at CTU in Prague.

| **Speed of tram [km h$^{-1}$]** | **Type A [-]/[ms]** | **Type B [-]/[ms]** | **Type C [-]/[ms]** |
|---|---|---|---|
| 10 | 37.0/0 | 44.6/0 | 43.7/0 |
| 15 | 49.7/0 | 49.7/0 | 49.8/0 |
| 20 | 65.3/0 | 83.7/2.1 | 71.8/0 |
| 25 | 83.3/1.9 | 121.4/7.3 | 99.2/4.5 |
| 30 | 97.7/5.1 | 142.1/8.2 | 127.2/6.7 |
| 40 | 115.4/8.2 | 174.7/8.5 | 173.4/8.1 |
| 50 | 155.4/12.9 | 213.3/8.1 | 210.9/8.2 |

Table 9. The evaluation of the 3 ms criterion for individual impact velocities for individual impact velocities and trams. The value in the table indicates the maximum value of the criterion and the time of exceeding the limit value.

The experience gained in solving this research will then be used in solving research on reducing the consequences of accidents of regional rail vehicles with cars at level crossing, which is addressed in the project TN01000026 at the same work place.

## List of symbols

$a$ acceleration [mm ms$^{-2}$]
$m$ mass of empty tram [kg]
$m_{col}$ collision mass of tram [kg]
$m_{pass}$ mass of passenger [kg]
$p_{seats}$ number of seated passengers [-]
$t$ time [ms]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