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**Research paper**

# Risk assessment for tram traffic on tramway bridges

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**Abstract:** Promoted by many cities to meet the commute needs of their residents (for work, education, etc.), urban rail transport is a spatially expanding system. The safety of rail passengers and road users is one of the most important factors to consider when designing the infrastructure and assessing the operation of the urban tram system. One of the unsolved issues in the functioning of tram transport are sections of tramways with large longitudinal slopes. The article presents an attempt to use risk management for assessing the operational safety of tramways located on road sections with large longitudinal gradients. This particular problem occurs on a tram route in Gdansk. It runs along a street (partly on an overpass) with a gradient above 5% and a small horizontal curve. Risk was assessed using TRANS-RISK, a risk management method. In the first stage, a risk analysis was carried out using the Bow–Tie methods and error trees. The main risks of serious accidents on the analysed section of the tramway were identified. Three sub-concepts were used to assess risk: individual, societal and collective. Although not generally used for assessments of urban transport infrastructure, the latter was found most useful for assessing the safety of the analysed infrastructure. The results of the analyses and assessments helped to formulate design and maintenance principles for tram infrastructure located on sections with steep gradients.

**Keywords:** tram infrastructure, sections with steep gradients, risk assessment, design guidelines

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# 1. Problem description

Urban rail transport which many cities are developing is a spatially expanding system designed to meet every day mobility needs of residents [17, 24]. The safety of passengers and other road users is an important factor to be taken into account when assessing the operation of rail transport systems.

A tram accident usually involves a single tram (overturning or hitting another object), two trams colliding or a tram colliding with a car, bicycle or pedestrian. The scientific literature gives limited information about tram accidents and their causes worldwide [2, 5].

Tram speeds are relatively slow in urban centres but can reach up to 80 km/h outside these areas. The main factors leading to tram accidents and their consequences are:

- trams drive into horizontal curves at excessive speeds while the curve's radius is too small, go over turnouts onto tramway crossings which most often results in tram derailments,
- high speed (e.g. on tracks located on a steep decline) and the presence of obstacles on the track (stones, screws, etc.) causing derailment,
- power failures and failures of the vehicle's electrical systems,
- brake failures or improper use of brakes by tram drivers,
- high wear and tear of the tracks or slippery track surface (e.g. leaves on rails),
- a vehicle or a pedestrian crossing the tracks within a short distance from the tram causing it to brake suddenly,
- vandalism of tram tracks,
- passengers trapped in doors or passengers falling out of the tram,
- difficulties in carrying out a rescue operation.

Analysis of tram disasters that occurred in the last century in selected countries [1, 4, 5, 7, 16, 19, 20] included what might be one of the most tragic accidents that took place in Argentina in 1930, in which 56 out of 60 passengers died when a tram plunged into a river while driving onto an open drawbridge. Another catastrophic accident was the 1996 crash in Ukraine, where out of 150 passengers 34 were killed and over 100 injured. The overcrowded tram during the rush hour derailed and crashed into a tram stop after its brakes failed while going down a steep decline. In Poland, the most tragic tram accident took place in Szczecin in 1962. Out of 500 passengers commuting to work during the morning rush hour 15 died and 150 were injured when the tram overturned as it was going down the track on a large decline located on a curve [7].

According to the cases presented, the most common cause of tram crashes was excessive speed causing derailment when trams travel on a small radius horizontal curve, a decline, a junction or even on a straight section [2, 3, 18]. An example of such an incident may be the well-documented accident in Croydon, London [20] in which a driver hit a horizontal curve that had a very small radius of $R = 30$ m which came after a long straight section on a slope. The tram was going at a speed ($Vr = 73$ km/h) significantly exceeding the speed limit ($Vd = 20$ km/h). As a result of loss of stability, the tram derailed and tipped over leaving 7 people killed and 62 injured. Tram crashes are often caused by a failure of the braking system when a tram descends a significant longitudinal decline. There were very dangerous tram accidents of this kind in Szczecin [7] and Kamiensko (Ukraine) when overloaded trams descended hills with failing braking systems.

Another case was the Gothenburg tram accident, where after a power failure and mistaken use of the brakes (the driver released the brakes activated automatically after a power failure), the empty tram began to roll downhill, and despite the police warning the public, the tram derailed at a tram stop and scooped people and vehicles like a plough. Additionally, fuel leaking from the wrecked cars caused fire. 15 people were killed and around 30 were seriously injured [16].

A similar incident took place in 2015 in Gdansk, in Bulonska Street. A technical vehicle was repairing damaged overhead lines when it was hit by a tram rolling downhill. The tram driver failed to use the brakes properly and crashed into the vehicle [10]. The event was the basis for undertaking this analysis and evaluation of tram safety on the tramway bridge in Gdansk which features a large longitudinal decline.

The project's research objective was to propose a method for assessing tram safety on tramways that are located on high longitudinal gradients and on engineering structures (tramway bridges). The practical objective of the project was to develop proposals for engineering and organisational measures to reduce the risks of hazardous events on tram networks in difficult terrain [10].

## 2. Research object and method

### 2.1. Research objective

In September 2015 a tram line was opened along Rakoczego Street in Gdansk. It connects Morena (a district of Gdansk) with the Pomeranian Metropolitan Railway's (PKM) Bretowo station. On a section of approx. 1.0 km the line runs along a longitudinal decline with varying gradients from 0 to 5%. At 0.3 km from the PKM stop, the line runs along a horizontal curve with a radius of $R = 180$ m. The tram line is connected to the PKM stop by a 362.1 m double-track overpass (Figures 1–4) with a gradient of up to 5%. It stands on thirteen spans, the highest

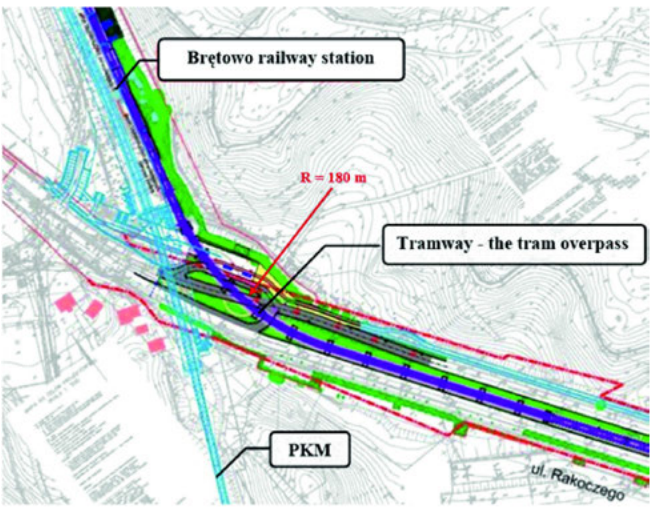


Fig. 1. Diagram of the analysed section of the tramway in Rakoczego street, Gdansk (horizontal alignment and vertical alignment) [10]

of which is 9 metres. The tram overpass runs in a curve with a radius of $R$ = 180 m and intersects the carriageway and pavement of Rakoczego St. at a grade-separated junction. It then runs parallel to the tracks of the Pomeranian Metropolitan Railway (PMR) at the Bretowo stop. The design speed for trams due to the horizontal curve (180 m radius) is 30 km/h. However, the permitted operating speed is $Vd$ = 15 km/h.

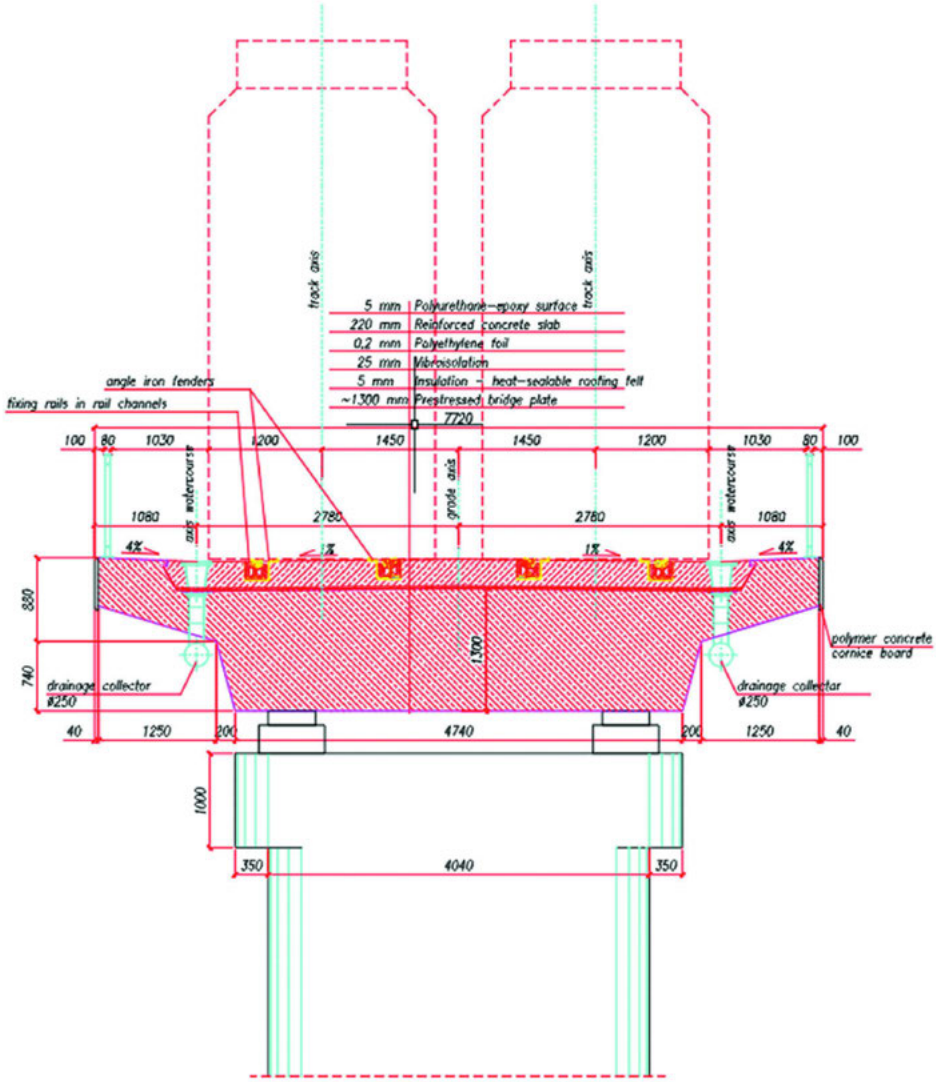


Fig. 2. Diagram of the cross section of the tramway road in Rakoczego St., Gdansk [10]

The tramway bridge's design rolling stock load is in accordance with PN 85/S-10030. The bridge's static system is made of a continuous, prestressed, 13-span slab with a width of 7.72 m

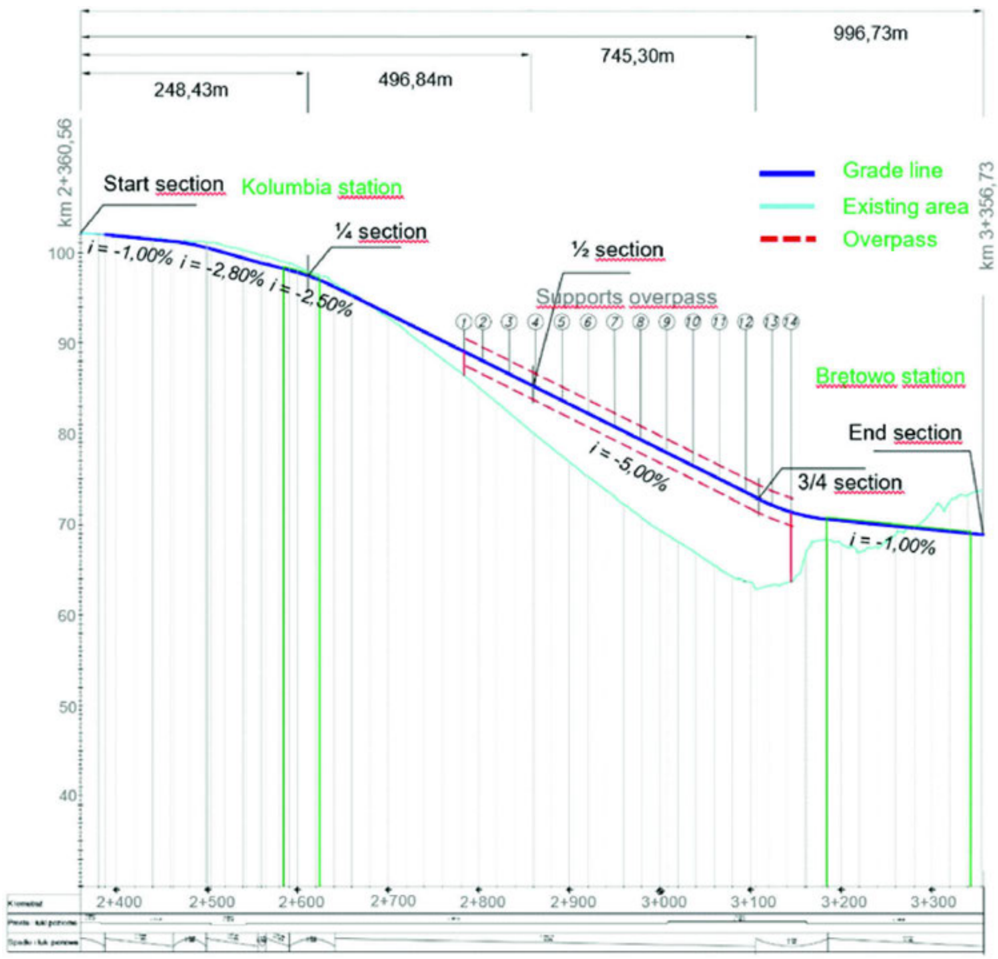


Fig. 3. Diagram of the vertical alignment of the analysed section of the tramway road in Rakoczego St., Gdansk [10]

Fig. 4. View of the tramway bridge in Rakoczego St., Gdansk. Source: press materials, trójmiasto.pl

of which 5.36 m (2 × 2.68) is occupied by the tracks. The tramway bridge is fitted with steel railings 1.1 m high on both edges fixed to the slab with concrete foundations.

The tram rails on the entire section of the tram bridge are set on a ballastless track surface structure, using a system of flexible continuous rails installed in a reinforced concrete slab made on site. This is known as embedded rail system.

The tram line is served by a double-ended fleet which does not require traditional terminal loops and allows trams to travel along routes with large longitudinal declines. In Gdansk this condition is met by two types of trams: Düwag N8C and PESA Jazz Duo.

For safety reasons, the speed limit on the analysed section of the tram line is 15 km/h, but the horizontal geometry of the tramway was designed for a speed of 30 km/h. An analysis of tram traffic shows that between 2 and 14 trams per hour pass through the section of the overpass on weekdays and 3 vehicles per hour on Sundays. Trams carry from 0 to 42 passengers per hour, which gives a yearly figure of approx. 105 thousand passengers [10].

## 2.2. The operational issues of the tram network

Based on data obtained from the Gdansk Road and Green Authority (tram infrastructure management) and ZKM Gdansk (transport operator), an analysis of operational problems on the tram network in Gdansk was carried out. Infrastructure failures and dangerous events during operation in the years 2012–2017 were identified. Aggregated data on undesired events are compiled in Table 1.

Table 1. Summary of data on overhead contact line failures and undesired events on the tram network in Gdansk in 2012–2017

| Year | Vehicle kilometres travelled | Number of overhead line/rectifier station failures | Number of undesired events on the tram network | Number of tram derailments |
|---|---|---|---|---|
| | VKT | NF | NE | ND |
| | (m vkm/year) | event/year | event/year | event/year |
| 2012 | 13.751 | 74 | 33 | 19 |
| 2013 | 13.782 | 88 | 29 | 17 |
| 2014 | 12.906 | 88 | 20 | 10 |
| 2015 | 13.200 | 90 | 24 | 12 |
| 2016 | 13.250 | | | |
| 2017 | 13.300 | | | |

Source: Gdansk Road Authority (GRA)

Particular attention was paid to incidents and failures that may lead to dangerous events. These incidents include network and power failures, brake system failures, and derailment of tram cars.

Network and power failures are causes of dangerous events, because tram vehicles lose their engine braking ability when they lose power. Annually, on the entire tram network in Gdansk there are approx. 80 such failures (i.e. on average, one failure per 1.2 km of tram tracks).

Efficient braking systems are the most important element of tram safety. Trams are usually equipped with the following braking systems: (1) in-service, engine braking during regular operation, (2) disc or block brakes when stationary, (3) emergency brakes used in an emergency, e.g. power failure. Failure of overhead contact lines and brake failure when a vehicle ascends/descends are the most detrimental type of events that can occur on the analysed section of the tram track. Table 2 gives a summary of undesired event indicators in the case of a power failure or derailment. Derailment may be caused by: damage or excessive wear of rails, damage or excessive wear of wheels, foreign material on tram tracks and excessive speed.

Table 2. Summary of undesired event indicators in Gdansk from 2012 to 2015

| Indicator | Overhead contact line/rectifier station failures | Undesired events on the tram network | Events related to derailment |
|---|---|---|---|
| Number of events NE (events/4 years) | 332 | 104 | 57 |
| Frequency of events FE (events/year) | 83 | 26 | 15 |
| Density of events DE (events/km/year) | 0.7 | 0.23 | 0.13 |
| Concentration of events CE (events/vkm) | $6.34 \cdot 10^{-6}$ | $2.06 \cdot 10^{-6}$ | $1.14 \cdot 10^{-6}$ |

Source: own study based on data from GRA

Because the analysed tram overpass is located on a steep incline of i = 5% and a curve with a relatively small radius of R=180 m, tram derailments are likely when the speed of 58 km/h is exceeded. If a tram were to descend uncontrollably, it may reach speeds of up to 120 km/h at the beginning of the analysed horizontal curve and derail.

During the analysed period, annually on the entire tram network there were 227 collisions and accidents, in which 36 people were injured. This means that on average per 1 km of the tram network, two hazardous events may occur each year involving an injury every 3 years. Table 3 gives a summary of hazardous event indicators on the tram network in Gdansk [10].

As we know from the literature, the effects of a tram car derailment can be significant: from damage to tram cars or other equipment in the vicinity, to fatalities among passengers, drivers or passers-by [1, 4, 5, 7, 16, 19, 20].

The design of the analysed overpass includes a system to reduce the effects of tram car derailment in the form of check rails made of steel angles placed in the rail beds. However, there is a lack of data on how effective the system is with preventing derailment and stopping trams from falling off the overpass, especially because the distance between the rail head and the check rail in the bed is very small (70 mm and smaller than the width of the tram wheel which is 90 mm), which may not be good enough to keep the car in the rail conduit in the case of a greater angle of approach or a higher speed.

Table 3. Summary of hazardous event indicators on the tram network in Gdansk from 2012 to 2015

| Indicator | Hazardous event (collisions and accidents) | Indicator | Casualties of hazardous events |
|---|---|---|---|
| Number of events NE (events/4 years) | 908 | Number of casualties NC (casualties/4 years) | 144 |
| Frequency of events FE (events/year) | 227 | Frequency of casualties FC (events/casualties/year) | 36 |
| Density of events DE (events/km/year) | 2.12 | Density of casualties DC (casualties /km/year) | 0.34 |
| Concentration of events CE (events/vkm) | $17.24 \cdot 10^{-6}$ | Concentration of casualties CC (casualties/vkm) | $2.74 \cdot 10^{-6}$ |

Source: own study based on data from (GRA)

The problems formed the basis for an analysis and risk assessment of the tram line operation on a tramway bridge located on a large decline and in a horizontal curve with a small radius [10].

## 2.3. Research method

There is not much available research on tram safety assessment. Most of the work focuses on assessing safety on existing tram networks [19, 23] or on producing expert reports after a spectacular tram accident [4, 16, 20]. There is a lack of methods for assessing the safety of new tramways, especially those operating in difficult conditions.

Attempts have been made to apply methods such as event tree, fault tree and Bow–Tie to identify hazards [6, 9, 14, 15, 21] and sources of hazards. The Risk Score method [13] was used to assess the level of safety on tram networks.

Risk assessment is a process of analysing and determining acceptable risk, taking into account accepted standards. Traditionally, risk assessment consists of risk analysis and risk evaluation. Risk analysis, the first step in the risk management process, is the systematic use of all available information to identify risks and to assess and prioritise them. The overall objective of risk analysis is to develop rational grounds for decision-making to avoid hazardous events and losses resulting from these events, which can occur anywhere, at any level of management in a specific transport system, on road section or road facility. Therefore, risk analysis should include: defining the purpose of the analysis, identifying the type and source of hazards and estimating the risk level.

Risk of safety hazard is a measure of the level of hazard, expressing both the probability of an event and the size of losses incurred as a result of this event. Safety is a state in which risk is not greater than tolerable risk. Tolerable risk is a risk that we are able to accept for one reason or both: little harm done and low probability of undesired event. The procedures proposed in the TRANS RISK assessment method were used to assess the safety status of the analysed tram infrastructure (tram overpass in Gdansk) [8, 9, 12, 14, 15]. The significant elements of this method are the identification of hazards and their sources, the evaluation of risks and the assessment of risk acceptability.

## 3. Tram hazard identification on a tramway bridge

Three methods were used to identify the risk of hazards: the event tree method, fault tree method and Bow–Tie method [6, 9, 14, 15, 21]. Fig. 5 shows a diagram of the cause and effect event sequence during the failure of an overhead line.

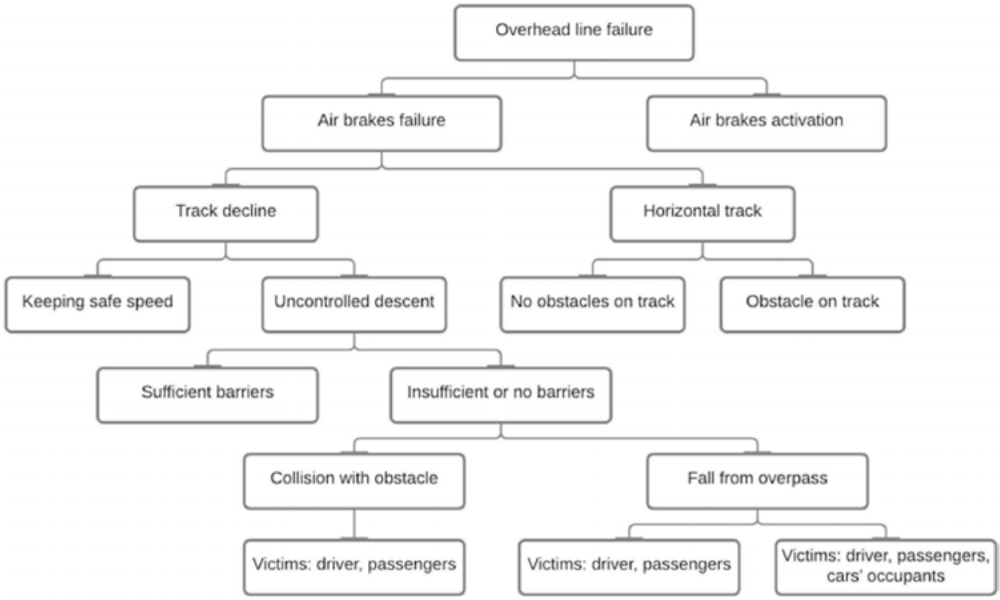


Fig. 5. The cause and effect event sequence during the failure of an overhead contact line – event tree [10]

The cause and effect sequence of events presented in the diagram shows that a failure of the overhead contact line may be the initiating dangerous event on the analysed section of tram tracks located on the overpass. Failure of a tram overhead contact line may cause the vehicle to come to a stop slowly when it is on a flat section of the track. However, where a tram is on a section of the track located on a longitudinal decline (during a power failure), the tram car may start to roll (unable to start in-service braking) in a controlled manner (with the possibility of safety or emergency braking) or uncontrolled manner (unable to engage any braking, e.g. failure or deactivation of the braking system).

When a tram is rolling uncontrollably, it may reach high speeds significantly above the safe speed [3, 22]. This may cause the following two dangerous events with catastrophic consequences:

– the tram derails and collides with a tram on the opposite track or hits a barrier or the tram falls off the overpass (approx. 10 m) and crushes vehicles on the street under the tram bridge (if there is no barrier or it has inadequate construction),
– or hits a tram located on the track below or a tram standing at a tram stop.

Each of these extreme cases may cause a disaster and significant material and social consequences (up to several hundred injuries or fatalities). Using the fault tree method, it was determined that a tram derailment could have several causes: damage to the rail, failure of the trolley (usually wheels) or foreign material on the tram tracks. Two cases of identified tram hazards along the analysed overpass were analysed using the Bow–Tie method [14, 21]: derailment of the tram and uncontrolled descent along a section with a high longitudinal decline. The latter case poses a major hazard because of the high speed a tram may reach as it travels down an elevation while moving uncontrollably. Figure 6 shows a diagram of the causes and consequences of uncontrolled tram descent on a tramway with a high gradient. The event was also analysed for its causes (Fig. 7). The analysis showed that this may be caused by a set of causes such as: technical failure of traction (traction breakdown or power cut), technical failure of the vehicle (braking system failure, uncontrolled descent), human factor (error or misuse of the braking system ), tramway design (high longitudinal gradients, small curve radius, lack of anti-derailment system, lack of safety barriers or no barriers). The analysis helped to identify and provide barriers to prevent the events from happening (elimination of causes) and take actions to mitigate the effects of hazardous events.

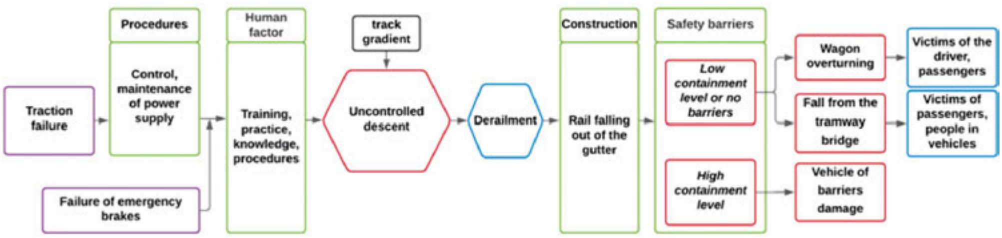


Fig. 6. An example of how hazards are identified in the case of a tram travelling uncontrollably on a tramway located on an embankment or overpass

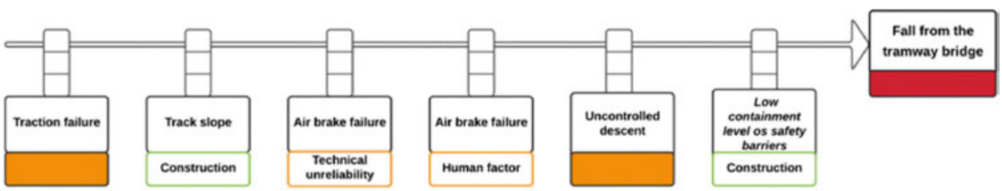


Fig. 7. Path from an initiating event to a selected consequence, a tram falling from an embankment or tramway bridge

# 4. Tram bridge risk assessment

## 4.1. Risk assessment method

The case under analysis involves operational risk related to the day-to-day activities of transport and maintenance companies. The risk occurs during tram service operation, i.e. in repetitive, well-known and well-understood situations which are carried out regularly. In general, operational risk is the consequence resulting from inappropriate or unreliable processes (tram traffic), people (traffic users), systems (infrastructure, trams and organisational system) and external events (weather conditions, vandalism, terrorism, etc.). The analysis and assessment were carried out for three types of risk: individual, group and societal [9]. Initially, safety analysis and assessment were conducted using two types of risk: individual and societal [9, 13]. Because the results differed from expert and intuitive assessments, the analyses also looked at group risk which is frequently used when assessing risk of air, sea and rail transport [8, 9] and of major accidents in chemical factories or flood control systems [25].

The methods under analysis use three basic parameters: risk exposure, probability of a hazardous event and the consequences of a hazardous event [9].

The exposure to the risk of a hazardous event depends on the number of tram journeys (Eq. (4.1)). Based on an analysis of the data on the current situation, the number of journeys per year was determined ($Vt = 60,000$ journeys/year) and vehicle kilometres travelled (for the section of the tram bridge with adjacent sections $L = 0.5$ km):

$$VKT = L \cdot Vt \tag{4.1}$$

where:

$VKT$ – vehicle kilometres travelled (vkm/year),

$L$ – length of the section analysed (km),

$Vt$ – tram vehicle volume (tram journeys/year).

After substituting the above data into Formula 1, the result was the numerical value of vehicle kilometres travelled at 30 thousand vkm/year.

Probability of a hazardous event. Further analyses used tram passenger load data which were developed on the basis of previous research by the authors. Next, tram traffic forecasts on the analysed line were developed for 2030 and the average daily distribution of tram passenger loads was determined (Fig. 8).

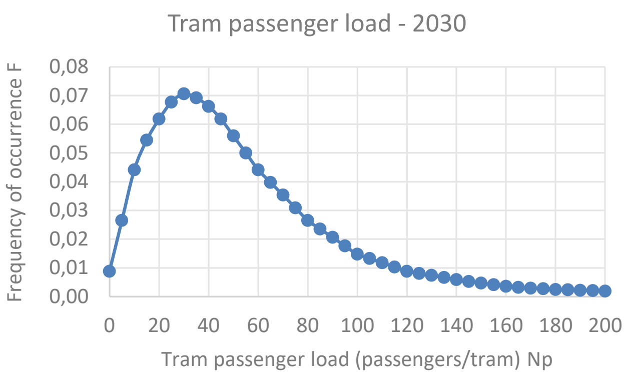


Fig. 8. Distribution of the daily tram passenger load on the analysed section of the line – forecast for 2030 [10]

Current research shows that at present the average tram passenger load is about 3 passengers on one tram journey with app. 20 passengers as the maximum value. Forecasts suggest a large increase in the number of passengers with the average passenger load at 54 passengers and the maximum value at up to 200 passengers per tram journey on the analysed section.

Table 4. Summary of the numerical values of the estimated probability levels of selected events on the analysed section of the tram line in Rakoczego St. (tram bridge section)

| Type of event | Probability of undesired events PUE (events/year) |
|---|---|
| Overhead contact line/rectifier station failures | $1.9 \cdot 10^{-1}$ |
| Undesired events on the tram network | $6.0 \cdot 10^{-2}$ |
| Events related to tram derailment | $4.0 \cdot 10^{-3}$ |
| Tram braking system failure | $5.7 \cdot 10^{-4}$ |
| Overhead contact line/ rectifier station failures and simultaneous tram braking system failure | $1.1 \cdot 10^{-4}$ |

Consequences of a hazardous event. The following assumptions were applied to estimate the consequences for each hazardous event scenario.

Material losses: (1) tram damage (destruction of a tram), estimated cost PLN 0.6–9.0 million, (2) damage to the overpass, estimated cost: PLN 0.2–1.0 million,

Table 5. Numerical values of estimated loss of selected hazardous scenarios on the analysed section of the tram line in Rakoczego St. (tram bridge section)

| Scenario | Type of hazardous event | | Material losses | Human losses, number of casualties | Economic losses costs of hazardous events |
|---|---|---|---|---|---|
| | | | | NC | CHE |
| | | | | (casualties) | (PLN m) |
| 1. | Driving within speed limit ($< 30$ km/h), tram derailment and remaining on the track | | Damage to tram and track | Minor injuries | 0.01 |
| 2.a | Uncontrolled driving, tram derailment and fall from the overpass | a) no passengers on tram, | Tram destroyed, several cars destroyed under overpass, overpass damaged | 1 – 10 | 12.5 – 35 |
| 2.b | | b) average number of passengers on tram, | | 55–65 | 150–170 |
| 2.c | | c) maximum number of passengers on tram | | 200–210 | 510–540 |
| 3.a | Uncontrolled driving, collision with other tram at high speed: | a) no passengers on trams, | Destruction of both trams | 2 | 15 |
| 3.b | | b) average number of passengers on trams, | | 110 | 285 |
| 3.c | | c) the maximum number of passengers on trams | | 400 | 1010 |

Social and economic losses (three variants): (1) minimal: 1 person (victims: driver), the cost of one fatal or seriously injured victim – PLN 2.5 million., (2) average: 55 passengers (victims: driver and 54 passengers), (3) maximal: (a) tram falling from overpass (victims: 1 driver, 200 tram passengers, 10 car passengers), cost PLN 525 million, (b) an uncontrolled descent of a tram and collision with another tram at high speed (casualties: 2 drivers, 400 passengers), cost PLN 1.1 billion.

Risk evaluation involves checking the risk acceptability class of a risk estimated during risk analysis (expressed in quantitative or qualitative terms). The following methods can be used to identify the limits of risk acceptance classes [9, 21]: (1) applying the existing standards of risk acceptance and rejection, (2) by engineering or expert assessments, (3) use of criteria values indicated in known qualitative risk assessment methods, (d) by estimating the limits of risk classes in quantitative risk assessment methods.

In the case of tram traffic, there are no classification methods or risk acceptance standards. As a result, it was proposed that standards adopted in other modes of transport should be used and applied to expert assessments. The risk classification used in other fields was accepted. In order to estimate individual and societal risk, the Risk Score method estimation and classification procedures were used.

However, in order to estimate the group risk (i.e. the risk of an accident occurring with the assumed number of victims), the proposed classification recommended for the EU was used [25].

### 4.2. Assessment of individual and societal risk

Individual risk refers to the behaviour of a single traffic user or a single vehicle on the analysed transport facility. Thus, it is the probability of suffering a consequence of a certain severity during a journey or during a selected period of time when the traffic user is exposed to a hazard from the transport infrastructure and other traffic users. This risk is used to identify factors that characterise variants of improvement and the targeted safety level for a given tram line. It also provides a basis for transport infrastructure authorities to maintain the assumed risk level depending on the class of the line and traffic volume. Individual risk can be controlled and its level can be effectively reduced. The mathematical model of individual risk in this case has the form (Eq. 4.2):

$$IR = P \cdot C \tag{4.2}$$

where:

$IR$ – individual risk,

$P$ – probability of hazardous event,

$C$ – consequences, individual losses in a hazardous event.

Societal risk refers to the behaviour of entire societal groups in a selected area. Therefore, it is a loss (number of casualties, as well as material losses incurred in road accidents) over an accepted period of time (usually per year), in a selected area (in this case the analysed tramway section located on the tram bridge), which may predictably occur as a result of hazardous events caused by the operation of the tram transport system. Societal risk provides the basis for transport authorities, city authorities and emergency services in a given area for taking decisions on how to improve the most hazardous elements of the tram transport safety system and how to utilise the projected safety budget in the most effective way [9]. The following societal risk model was assumed (Eq. 4.3):

$$SR = E \cdot P \cdot C \tag{4.3}$$

where:

$SR$ – societal risk,

$E$ – exposure – represents a quantitative measure of the exposure of traffic users to a potential hazard (e.g. vehicle kilometres travelled),

$P$ – probability of a hazardous event,

$C$ – consequences of hazardous events or the level of losses in hazardous events.

On the basis of own research [8, 9] and foreign experience, a risk classification (based on the Risk Score method) for the safety of tram traffic in Gdansk was developed. Table 6 presents a proposal for classifying societal and individual risks, risk acceptance levels and proposals for preventative actions (eliminating or reducing the level of risk). Table 7 presents the results of risk assessment for the different scenarios of hazardous events occurring on the analysed section of the tramway.

Table 6. Point criterion for estimating the class of societal and individual risk and its acceptance level for the analysed tramway

| Risk category | | Risk category level | Risk acceptance level | Preventative actions |
|---|---|---|---|---|
| Societal risk | Individual risk | | | |
| $SR \le 20$ | $IR \le 2$ | negligible | Acceptable | Control recommended |
| $20 < SR \le 70$ | $2 < IR \le 7$ | low | Tolerable | Control needed (necessary) |
| $70 < SR \le 200$ | $7 < IR \le 20$ | significant | | Improvement needed |
| $200 < SR \le 400$ | $20 < IR \le 70$ | high | Unacceptable | Immediate improvement needed |
| $SR > 400$ | $IR > 40$ | very high | | Recommended to suspend service until significant improvement |

Analysis of the results shows that individual and societal risks of tram derailment when the tram travels down a slope at low permitted speed (scenario S.1) are low and fall within the acceptable risk range. Individual and societal risk of hazards related to an uncontrolled tram descent (scenarios S.2 and S.3) vary from low to very high and are in the area of acceptable or tolerable risk.

Recommendation: the analysed facility should be under supervision and its operation, including the trams, should be systematically monitored, a set of improvements reducing the risk to an acceptable level should be introduced.

Table 7. Point criterion for estimating the class of social and individual risk and its acceptance level for the analysed tramway and tramway bridge

| Events | Risk components by Risk Score (points) | | | | | Risk assessment level | |
|---|---|---|---|---|---|---|---|
| Scenario | Probability | Consequences | Risk Exposure | Risk (points) | | Individual risk | Societal risk |
| *S* | *P* | *C* | *E* | *IR* | *SR* | *IR* | *SR* |
| 1. | 1 | 1 | 6 | 1 | 6 | Negligible | Negligible |
| 2.a | 0.2 | 40 | 6 | 8 | 48 | Significant | Low |
| 2.b | 0.1 | 100 | 10 | 10 | 100 | Significant | Significant |
| 2.c | 0.1 | 100 | 6 | 10 | 60 | Significant | Low |
| 3.a | 0.2 | 40 | 6 | 8 | 48 | Significant | Low |
| 3.b | 0.1 | 100 | 10 | 10 | 100 | Significant | Significant |
| 3.c | 0.1 | 100 | 6 | 10 | 60 | Significant | Low |

## 4.3. Collective risk assessment

Collective risk refers to a group of people at or near the site of a hazard and is defined operationally as the probability of more than the $N$ number of fatalities in a single hazardous event. Collective risk provides a basis for transport infrastructure authorities to decide how to improve the most vulnerable elements of the transport network and how to utilise the projected budget in the most effective way. Collective risk can also be used to assess the safety of the planned transport network so decisions can be made as to actions necessary to ensure safe design of transport infrastructure facilities.

Probability level $F_{(N)}$ of the occurrence of the $N$ number of fatalities in a single accident was assumed as the stochastic measure of collective risk. The general model of group risk can be formulated as follows (Eq. 4.4):

$$CR = F_{(N)} \cdot N^a \tag{4.4}$$

where:

$CR$ – collective risk,

$F_{(N)}$ – probability of N-number fatalities in a hazardous event,

$N$ – projected number of fatalities in a hazardous event,

$a$ – risk aversion coefficient.

In the case of collective risk, the EU recommendation [25] was used and a classification dedicated for the needs of tram traffic safety assessment was proposed. Its boundaries are shown in Figure 9. Group risk assessment involves the following steps:

- identify: hazards and scenarios of the most hazardous events,
- estimate possible losses, probability of losses,
- establish the level of group risk acceptability.

From the set of hazards analysed, the most significant risk of a possible dangerous event was selected, i.e. uncontrolled descent of a tram over a sloping tramway with the tram falling from the overpass or crashing into a tram which is standing at a stop or travelling on the adjacent track. The results may be catastrophic.

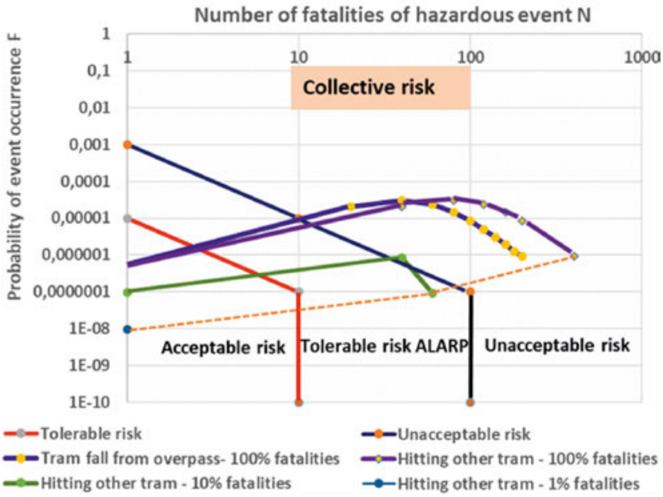


Fig. 9. Distribution of the daily tram passenger load on the analysed section of the line – forecast for 2030 [10]

The measures of collective risk were calculated as the probability quotient of the occurrence of the $N$ number of $F_{(N)}$ fatalities in a dangerous event and the forecasted (predicted) number of fatalities $N$ in a tram accident using the Formula (3). The number of tram accident casualties depends on the number of passengers on the tram and the number of people in the area of impact (tram derailed, falling off). Several variants of the tram passenger load were assumed in the analysis.

The probability of the $N$ number of $F_{(N)}$ fatalities in a hazardous event depends on the frequency of events initiating a given type of tram accident and the number of tram journeys on the analysed section of the tramway with the assumed passenger load. Based on the analysis of historical tram accident data, it was assumed that a dangerous event involving a power outage and failure of the braking system of a tram moving down a slope may occur once every 30 years.

Figure 8 presents graphs of changes in the probability of the potential number of fatalities depending on the number of passengers in the tram (the forecasted passenger load for 2030 was assumed) and the type of a possible hazardous event as a result of an uncontrolled tram descent (falling from an overpass or hitting another tram) [16] against the assumed acceptability limits of group risk.

Using the risk accessibility limits shown in Fig. 9, the level of risk acceptability of a certain number of fatalities in a tram accident was determined. The presented results indicate that the effects of one hazardous event occurring in 30 years, involving an uncontrolled descent of a tram on a steep tramway and falling from an overpass or hitting another tram, poses a very high risk to passengers even at a moderate tram load. In these cases, the **collective risk** of a tram safety hazard on the analysed section of the tramway will be **at an unacceptable level**.

# 5. Response to risk

The research and analyses have helped to formulate a course of actions to eliminate the identified hazards or reduce their effects when a dangerous event occurs.

The risk of derailment when the tram travels at permitted speed is low and is within the acceptable risk range. However, it was recommended that the existing safety system should be enhanced to prevent a tram from derailing, and if it derails it should be prevented from moving across the cross-section of the overpass and falling from the overpass.

The risk of hazardous events caused by an uncontrolled descent down the steep tramway varies from low to very high. The results of the assessment **of individual risk** (for a single hazardous event) and societal risk (for all hazardous events during the year) on the analysed facility indicate that the estimated risk is within an acceptable or tolerable range, i.e. that the analysed facility should be under supervision, its operation including trams should be systematically monitored, and a set of improvement measures should be introduced to reduce the risk to an acceptable level.

The results of **collective risk** assessment (the risk of a single hazardous event on the analysed facility with severe consequences) suggest that the estimated risk may be within the tolerable or unacceptable range. This means that the following actions should be taken:

1) the analysed facility should be placed under systematic control, its operation including tram traffic should be monitored,
2) speed management to prevent excessive speeds should be introduced (e.g. by applying the braking system) on the approach to the curve and on the curve of the track,
3) temporarily limit the maximum number of passengers on the tram and introduce tram traffic rules to ensure that a tram rolling down the tramway does not hit another tram,
4) develop safety systems to prevent tram derailment and, if it a tram derails it should be prevented from moving across the tram overpass cross-section and falling from the overpass or hitting another tram.

The results of the analyses and evaluations also indicate the need for a detailed analysis of what can be done to reduce the probability of the risks materializing and to reduce the consequences if the risk materialises. In addition, similar analyses and risk assessments were recommended on other sections of the tram network in Gdansk, in particular with steep longitudinal gradients. Taking into account the proposed recommendations, the mayor of Gdansk commissioned a safety inspection of the entire tram network (105 km) in Gdansk [11] at the end of 2016, the results of which will be the subject of further publications by the authors.

Using the method four other steep tramway sections were identified with a high or very high group risk of derailment. Additional measures were proposed to reduce the probability of such events:

1. Systematic checks of the technical condition of electric traction and the power supply system to be undertaken by tram infrastructure maintenance staff to eliminate faults and breakdowns of the technical infrastructure.
2. Systematic technical control of trams by the carrier's maintenance staff to eliminate faults of emergency brakes used in trams.
3. Systematic training for tram drivers, maintenance staff and supervisory staff to eliminate human error.

4. Use of an automatic system for tram traffic control (speed control and distances between trams, tram traffic control using special braking systems, e.g. by using external trackside active or electrodynamic brakes on steep sections, in particular before approaches to horizontal curves and on the entire curve section [22].
5. Put up barriers to prevent trams from falling off the overpass, e.g. road safety barriers type H4b, on the entire length of tram overpasses and high embankments (at least along horizontal curves on overpasses); this will help to contain a tram when it hits a barrier at a speed below 55 km/h.

## 6. Conclusions and summary

On the basis of the analyses, the following conclusions were drawn:

1. Tram engineering facilities should be designed with special attention to and use of risk analysis for tram transport to assess the operation of the designed facility. A negative example of such a structure is the tramway road and bridge in Rakoczego St. in Gdansk, which may contribute to a serious risk of tram accidents.
2. The location of tram tracks on sections with a fairly large longitudinal decline, and in particular on an overpass ending with a small radius horizontal curve, may contribute to the occurrence of two undesired scenarios of hazardous events: tram derailment at normal operating speed or uncontrolled descent down the overpass due to simultaneous power and braking system failure.
3. The analyses indicated that in order to assess the safety of tram traffic, it is necessary to analyse three types of risk: individual, societal and collective. In the studied case, the analysis showed that: the risk of a hazardous event caused by uncontrolled tram descent down a steep tramway can be:
   – social and individual at an acceptable or tolerable level;
   – collective at an unacceptable or tolerable level;
4. The adopted methodology of risk analysis and assessment is recommended for evaluating the operational safety of tram infrastructure facilities in other cities.
5. Following the risk assessment, it was clear that immediate actions were required to eliminate the risk of hazardous events and to limit their consequences. They included a 15 km/h speed limit on the analysed section and a proposal to use anti-derailment equipment and rules for the supervision of tram traffic on the analysed section.

Taking into account the proposed recommendations, the mayor of Gdansk commissioned a safety inspection of the entire tram network (105 km) in Gdansk at the end of 2016, the results of which will be the subject of further publications by the authors.

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# Ocena ryzyka ruchu tramwajowego na inżynieryjnych obiektach tramwajowych

**Słowa kluczowe:** infrastruktura tramwajowa, odcinki o dużych pochyleniach, ocena ryzyka, wytyczne projektowania

## Streszczenie:

Miejski transport szynowy wielu miastach stanowi istotny element systemu transportowego i jest przestrzennie rozwijającym się systemem zapewniającym mieszkańcom codzienną obsługę transportową. Bezpieczeństwo pasażerów transportu szynowego i użytkowników dróg jest jednym z najważniejszych czynników, który należy uwzględnić w trakcie projektowania infrastruktury oraz w ocenie operacyjnej systemu miejskiego transportu tramwajowego. Jedną z nierozwiązanych kwestii funkcjonowania transportu tramwajowego są odcinki dróg tramwajowych o dużych pochyleniach podłużnych. W artykule przedstawiono próbę zastosowania metody zarządzania ryzkiem do oceny bezpieczeństwa funkcjonowania dróg tramwajowych na obiektach zlokalizowanych na odcinkach dróg o dużych pochyleniach podłużnych. Taki problem występuje na trasie tramwajowej w Gdańsku przebiegającej na ulicy (częściowo na estakadzie) o pochyleniu położonej powyżej 5% i małym łuku poziomym. Do oceny ryzyka zastosowano metodę zarządzania ryzykiem w transporcie TRANS-RISK. W pierwszym etapie przeprowadzono analizę ryzyka zagrożeń, korzystając z metod Bow–Tie i drzewa błędów zidentyfikowano główne zagrożenia poważnymi wypadkami na analizowanym odcinku drogi tramwajowej. Do oceny ryzyka zastosowano trzy podejścia oceniając ryzyko: indywidualne, społeczne i kolektywne. To ostatnie, nie używane w tego typu ocenach miejskiej infrastruktury transportowej, okazało się najbardziej przydatne do oceny bezpieczeństwa analizowanej infrastruktury. Wyniki przeprowadzonych analiz i ocen pozwoliły na sformułowanie zasad projektowania i utrzymania obiektów infrastruktury tramwajowej położonej na odcinkach o dużych pochyleniach.

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