PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **12, 1 (43), 2021, 9-26**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Conceptual Design of an Anti-collision System for Light Rail Vehicles

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Received by the editorial staff on 30 March 2020
The reviewed and verified version was received on 21 February 2021

DOI 10.5604/01.3001.0014.7848

Abstract. This paper presents the concepts for an anti-collision system intended for trams. The purpose of the anti-collision system is to develop and provide information to support the driver's decision to initiate the braking of a tram. The anti-collision system is based on the processing of data from multiple sources (obstacle detection, image processing, and visual light communication system) and an expert system. The information about the road situation is visually presented on HUD (*Head-up Display*) of the driver.
Keywords: mechanical engineering, anti-collision system, obstacle detection system, image recognition system, expert system.

1. INTRODUCTION

The direct cause of increased traffic intensity is the civilizational growth of societies. As urban agglomerations expand, the traffic infrastructure which enables people to commute and the transport of goods follows suit. An analysis of the traffic structure in most cities leads to the conclusion that the public transport service lines are extended radially to connect the opposite ends of the city. Transport lines usually concentrate in the central parts of an agglomeration to allow commuters to change their direction of travel. These critical traffic hubs merge bus service lines, tramway service lines, and the roads, as well as inter-city traffic links. This traffic architecture makes the city centres highly congested, with considerable obstructions to traffic. Considering the safety of residents and the functioning of a city, the uninterrupted throughput of traffic lines has become a major issue, one which affects economic growth, the environment, and the health and well-being of people.

A collision involving a public transport vehicle can paralyze urban traffic and generate losses, the significance of which is often outside of human awareness. Property losses aside, the critical issue is the injuries resulting from the collision. Despite the low speed of vehicles which moving by urban areas, traffic accidents which involve a public transit vehicle result in a relatively high number of injured people [1]. One example is the collision of three trams in Poznań, Poland, in December 2018, which left 20 people injured [2]. Another traffic accident in Warsaw, in October 2018, was the collision between two trams in which approximately 10 people were injured [3]. A head-on collision between two trams on 2 January 2019 in Warsaw caused injuries to 13 passengers, with four severely injured [4].

A wider analysis of the news in the Internet uncovers a great number of tramway collisions, always with multiple injuries, plus fatalities in extreme cases.

This problem is one with global awareness. Several countries, like Poland, the United Kingdom, Austria, Norway, Germany, and France, undertake reporting of traffic incidents [5-10]. An explicit example is provided as the data in Table 1.

Traffic collisions cause property losses as a result of damage to the public transit vehicles and infrastructure. Tangible losses aside, there are additional costs suffered by urban residents. Accidents in urban areas can paralyse city traffic, cause jams, stress and unnerve residents, commuters, and drivers, delay supply chains and arrivals at workplaces, increase exhaust gas emissions and noise from vehicles, and the sense of danger in people, tangible losses which remain virtually unaccounted for by those exposed to them.

Table 1. Number of selected hazardous traffic incidents with tram cars and other road traffic actors in Poznań (Poland), in a specific range of years [9]

#	Incident description	Incidents per annum			Total of incidents
		2012	2013	2014	
1.	Accidents with casualties (hitting, running over, jumping on/off a tram car)	81	68	68	217
2.	Collision with another tram car or bus	20	10	15	45
3.	Collision with motor vehicles	339	334	238	921
4.	Accidents with intoxicated pedestrians/passenger casualties	11	12	15	38

Many private companies undertake research into solutions which can minimise the risk of traffic collision. They include Bosch, Siemens, and Bombardier Transportation (Fig. 1).

a) b)

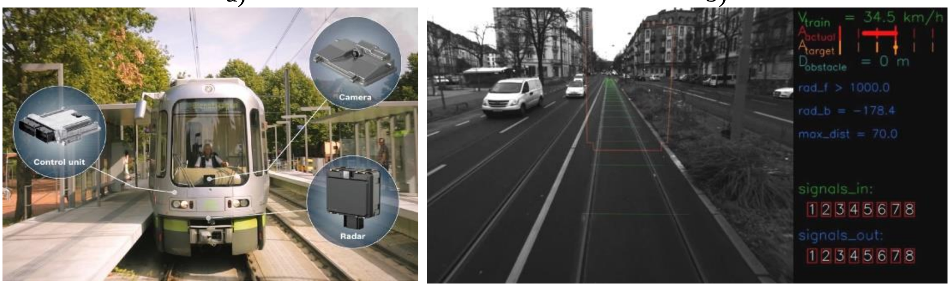

Fig. 1. Examples which illustrate the development of tramway anti-collision systems: (a) from Bosch and Siemens; (b) from Bombardier Transportation [11, 13]

The anti-collision system developed by Bosch and Siemens is dedicated to tram (LRV cars), comprising a video camera, radar, and control unit [11-12]. The purpose of the anti-collision system is to develop and provide visual and auditory feedback to support the driver's decision to initiate braking of a tram. The DAS (*Driver Alert System*) from Bombardier Transportation is an anti-collision system which warns a tramway driver of the potential collision with pedestrians, motorcyclists, other vehicles, or objects in obstruction of the tramway tracks. The system operated by a network of stereo cameras to identify and track the motion of objects in the vicinity of tram's trajectory. If a potential collision is identified by the system, it issues auditory alarm for the tram driver and can automatically brake the tram to stop. [13].

Considering the above, it seems indispensable to make changes in Poland and to improve the traffic safety of vehicles, especially trams, since the traffic incidents involving them are particularly difficult in terms of maintaining continued flow of urban public transit.

One of the methods for the reduction of traffic collision risks is the application of anti-collision systems aboard tram. Trams are LRVs (*Light Rail Vehicles*) exceptionally at risk of running over obstacles, vehicles, and people, since the trajectory of a tram is restricted to the rail track and the tram car is not capable of any evasive movement. Head-on collision with other vehicles are a risk particularly high when separate rail tracks cross one another. The examples listed above do not include traffic incidents caused by non-rail vehicle entry on a tramway track or people stepping on tramway tracks; These cases can lead to considerable losses.

Having analysed the aspects discussed so far, a set of characteristics was defined that a traffic safety system for trams should have. The solution proposed in this paper should first ensure the determination of information about the distance between the vehicles in motion. Another essential characteristic is the determination of the differential speed between the leading vehicle and the following vehicle. The last characteristic is the operating speed of the incoming (following) vehicle, a parameter of considerable importance to the vehicle's traffic safety if the leading vehicle and the following one are a small distance apart. The anti-collision system should provide alerts to the tram car driver whenever the distance between the vehicles is less than 50 m. This data should be determined with passive and active measures, which include measurement of traffic parameters and communication between the vehicles in traffic.

It seems that one of the most significant requirements for the development of an LRV traffic safety system is the application of passive measures, capable of detecting the distance to obstacles ahead and determine the traffic parameters without change the vehicle's structure.

Active solutions which operate by way of data communication between the trams in traffic and the tramway infrastructure (tram stops, catenary masts, and tram cars) are not discounted here. In the anti-collision system solution presented in this paper, active emission of RF waves for communication between trams was abandoned in favour of a visual light communication system. The vehicle's traffic parameters will be determined by an inertial measurement unit and encoders installed on the wheel trucks of the LRV (to measure the distance covered and the operating speed of the vehicle).

The anti-collision system with the features listed above is dedicated for new and retrofitted trams alike, without influence for the vehicle's structure and only with minimum interference with the tramway infrastructure. On-board GPS navigation modules will be used in the anti-collision system (as a considerable fraction of all trams in operation have GPS receivers installed). The GPS navigation modules will, under specific circumstances, determine the vehicle's position and correct the indications of other systems.

The last of the design requirements is a relatively low production cost of the anti-collision system, the value of which should be acceptable for the modernization of trams.

The action was undertaken by the Military University of Technology (Warsaw, Poland) in cooperation with INTECO, a private corporation [14].

2. CONCEPT OF THE LRV ANTI-COLLISION SYSTEM

The following design requirements were adopted for the implementation of the LRV anti-collision system:

1. The system must operate continuously to support the decision-making process of the LRV driver.
2. The LRV must have a data transmitter and receiver, which transfer information about move parameters of trams.
3. The LRV-to-LRV communication should be based on a code transmitted by a VLC (*Visual Light Communication*) system.
4. The threshold distance between LRVs that generates warnings for the driver is 50 m.
5. The detection of obstacles ahead of the LRV should be based on a video image processing system (HOG – *Histogram of Oriented Gradients*).
6. The detecting of an optical graphic marker (ArUco) should be used to reset the anti-collision system.
7. The inertial measurement unit (IMU) should measure motion parameters of the tram.
8. The GPS navigation receiver should obtain a position of the tram.
9. The messages should visualize for the driver of tram by HUD (*Head-up Display*).
10. The components of the anti-collision system should be integrated over a CAN bus network.
11. The driver's decision assistance should be processed and resolved by an artificial intelligence solution (an expert system).

Reference literature is available concerning VLC [15-24]. This paper presents a proprietary concept of an LRV anti-collision system.

The concept of the LRV anti-collision system presented in the paper is based on the following event scenario. The LRV (tram) departs from a tram stop, passing a Road Start marker (with ArUco encoded information and posted at the tram stop or the nearest catenary mast ahead, for example).

When the tram detects the Road Start marker, the determination of the distance covered by the LRV begins. The value of distance covered is measured by IMU (*Inertial Measurement Unit*) and/or encoders of the tram.

When the tram is approaching another tram, while the distance between the two is more than 50 m, the tram's anti-collision system should not issue any warning/alert. If the distance to the tram ahead becomes 50 m or less, the communication system between the tram should be activated and the following tram should receive the distance covered and speed data from the leading tram (Fig. 2).

At the same time, the video imaging system determines the distance between the trams if there isn't communication between the trams. The distance threshold of 50 m between the LRVs is imposed by the range of light between the leading rear of the tram and the following LRV's headlights, assuming an average operating speed of the tram about 35 km/h.

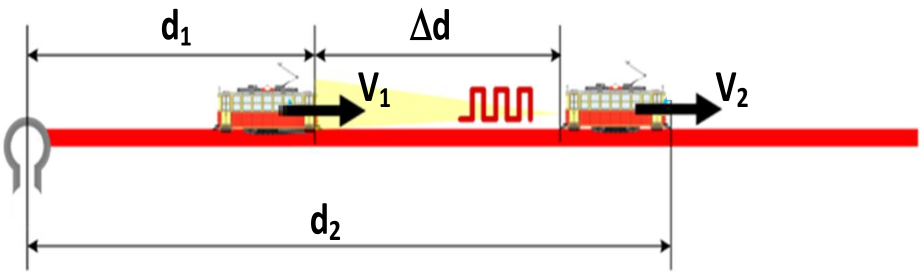

Fig. 2. Diagram of LRV-to-LRV communication and the essential performance parameters of the LRV anti-collision system

The average estimated tram operating speed was assumed to be 35 km/h from the tests performed during the development of the tram anti-collision system and the available reference data on trams operating in urban traffic (Fig. 3).

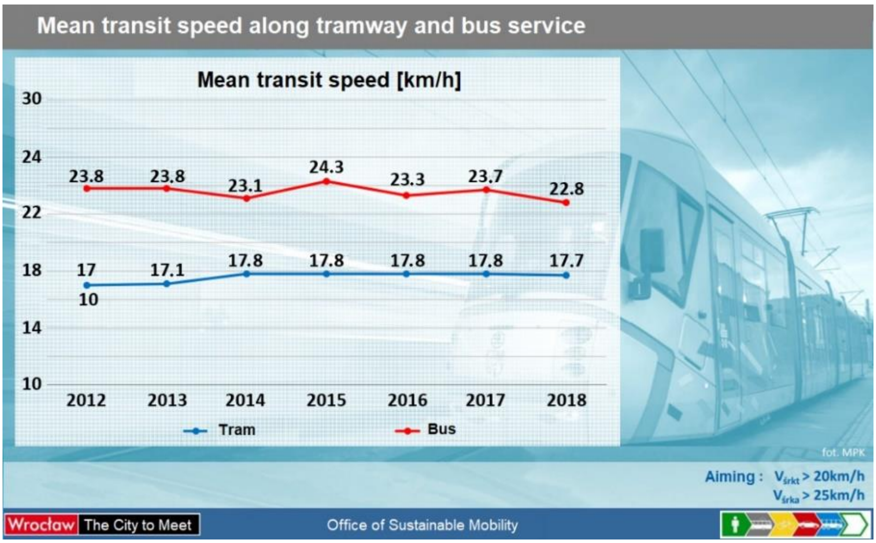

Fig. 3. Chart of average operating speeds of selected public transit vehicles [25]

Based on the estimated traffic parameters of the leading and the following tram, and the LRV-to-LRV distance, the following measures are determined by the system:

Δd – LRV-to-LRV distance,
Δv – Differential speed between the leading tram and the following tram,
v_2 – Operating speed of the following tram.

The parameters are relayed to the decision-assist system, which accordingly outputs the messages for the tram driver. The messages are shown on a HUD.

3. ANTI-COLLISION SYSTEM COMPONENTS

The core components of the LRV anti-collision system include:

- Obstacle detection system,
- VLC system,
- Image processing system,
- Information display,
- Decision-assist system (expert system).

3.1. Obstacle detection system

The value of the LRV-to-LRV distance is determined by a video imaging system, which comprises a video camera and a computer unit. The raw data source for this system is the video camera feed, which records image frames and sends them to the computer unit. The video feed is processed and the result of the visual information, being the LRV-to-LRV distance, is relayed over the CAN bus to the decision-assist expert system. The video imaging system must conform to these requirements:

- High performance of the system is expected and depends on the image analysis method and hardware implementation;
- The requirements for the variable condition of illumination during image recording (Fig. 4);

(a) (b) (c)

Fig. 4. Photographs which show differences in illumination conditions:
(a) morning; (b) evening; (c) night

- The system must be capable of recognising different types of obstacles to which the tram's distance is to be measured;
- The system must be capable of discriminating different types of terrain (without any pattern present and with differences in appearance resulting from different illumination conditions).

The distance from the obstacle on the track ahead (e.g. a leading tram) is based on information about the track gauge at the location obscured by the obstacle. This solution can be implemented since the track gauge is fixed and known, and thus the distance from the video camera and the obstacle can be calculated. This is achieved by the following relation (1)

$$D = \frac{f \cdot R \cdot imW}{H \cdot P}, \tag{1}$$

with:

D – distance to the obstacle [mm];
f – focal length [mm];
R – track gauge [mm];
imW – image FOV width [px];
H – video imaging array width [mm];
P – width measured in the image [px].

The method's operating result is information about the number of image display pixels at the obstacle. Considering (1), it is possible to determine the LRV-to-LRV distance (Fig. 5).

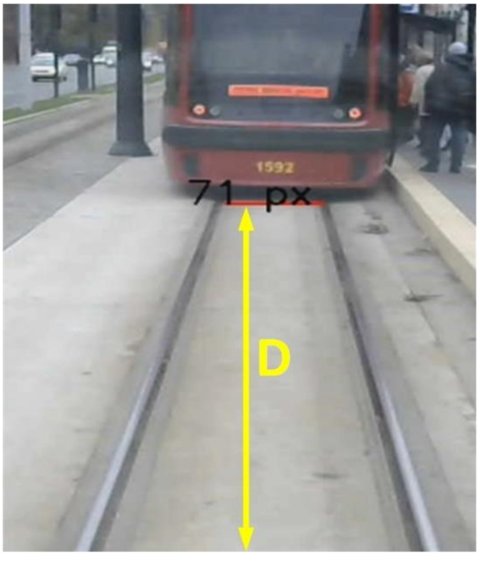

Fig. 5. Illustration of the obstacle distance determination method

3.2. Image processing system

A critical component of the anti-collision system is its image processing system, which uses optical systems based on video cameras. The purpose of the image processing system includes determination of the host tram's position and acquisition of the location in the tramway infrastructure in which the tram stops. The special algorithm is implemented for the identification of ID of ArUco markers [26]. It was decided to implement ArUco markers due to their simple design, which permits quick and reliable, error-free detection. The greatest advantage of ArUco markers is the capability of determination of the image processing system's position in relation to the marker being detected by recognition of just one marker in the field of view. Examples of ArUco markers are shown in Fig. 6.

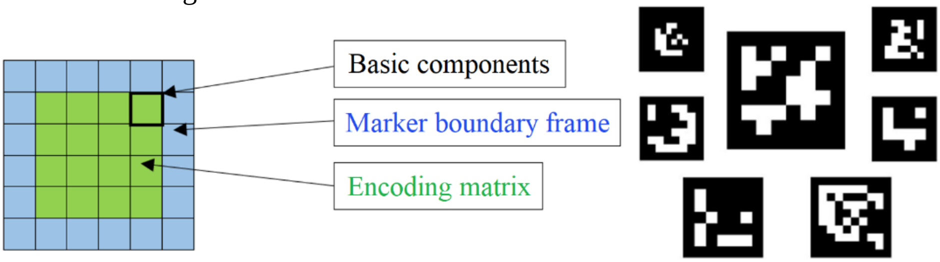

Fig. 6. Components of an ArUco marker and examples of its encoding matrices

3.3. VLC system

Another key problem of the project is to ensure data/information exchange between trams and between trams and their infrastructure. The relay of the information concerning the traffic parameters of the leading tram markedly improves the reliability of the distance measurement by the video imaging system. The communication medium is visual light. It is a data carrier safe to human eyes, as each tram is fitted with white light headlights and tail lights (due to type approval requirements), which makes the implementation of a VLC viable. The headlights which illuminate the tracks ahead of the tram while indicating the presence and clearance (envelope) of the tram can be used to relay information.

The information transmitted by VLC is encoded by modulating the light output intensity within a wave frequency band not perceived by the human eye (Fig. 7). The information to be output by VLC is relayed via the CAN bus and Manchester-encoded.

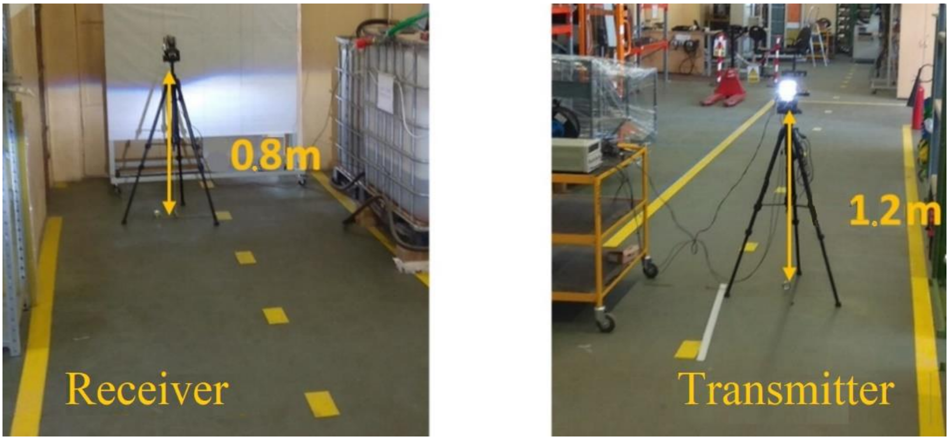

Fig. 7. VCM system's test rig components

3.4. Head-up Display

HUDs (*Head-up Displays*) which provide information output at the height of the operator's eyes are mainly applied in aerospace. However, HUDs have been appearing in vehicles. Image projector designs are available with special anti-ghosting windshield films which allow HUD applications in trams at a relatively low capital expenditure. Fig. 8 shows an example form of information output which advises the tram driver to start braking.

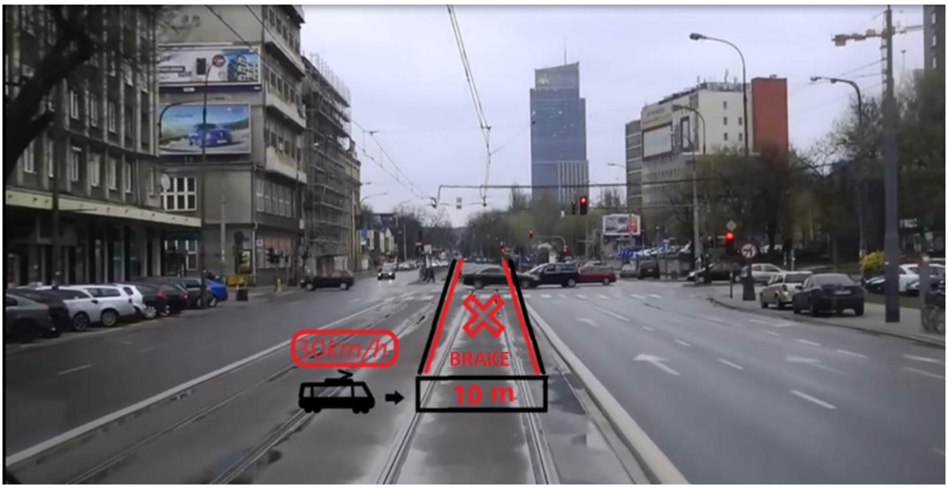

Fig. 8. Example of the information output for approaching an obstacle

The information display system provides four messages to the tram driver:

– Go – (green) the track ahead is open,
– Warning – (yellow) an obstacle is detected ahead, but the distance and traffic parameters do not indicate a hazard,
– Brake – (red) an obstacle is detected and tram's speed must be reduced,
– Service Mode – (blue) the system is offline.

3.5. Decision-assist system (expert system)

The mission-critical component of the tram anti-collision system is an expert system which decides what message is to be fed back to the driver via the HUD. The evaluation of traffic parameters uses an application of the fuzzy logic theory [27, 28]. A characteristic property of fuzzy logic is the attribution of a defined value to a membership function. Fig. 9 illustrates the block diagram of the decision-assist system adopted for the tram anti-collision system. To attempt the implementation of this system, it was necessary to identify the signal normalization methods and establish a knowledge base of rules and fuzzy logic functions.

As indicated in the Introduction, the expert system receives three input parameters. The expert system outputs one value which indicates which of the possible messages is to be fed back via the HUD.

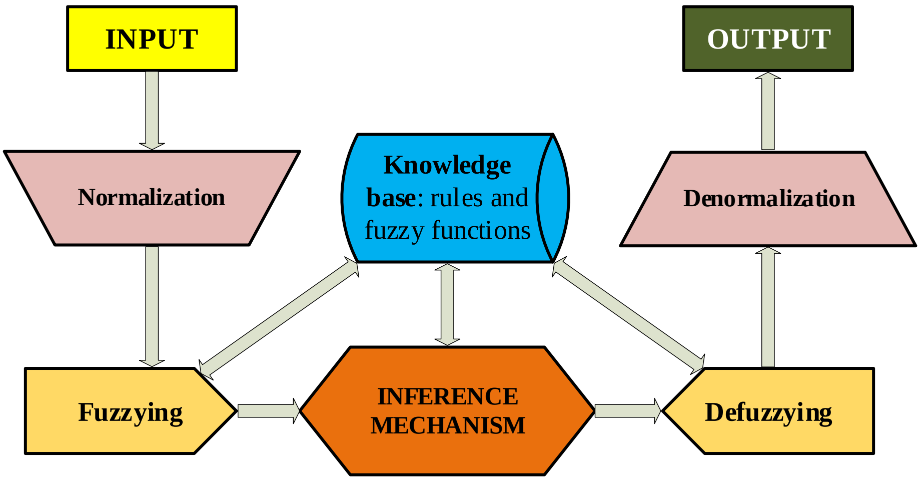

Fig. 9. Block diagram of the decision-assist system adopted for the LRV anti-collision system

Once normalized, each of the input parameters has a value within the following range:

– LRV-to-LRV distance Δd_n:

$$\Delta d_n \in \langle 0,1 \rangle;$$

– differential speed Δv_n:

$$\Delta v_n \in \langle -1,1 \rangle;$$

– operating speed v_{2n}:

$$v_{2n} \in \langle 0,1 \rangle.$$

The membership functions are defined for each input parameter. The fuzzy set of LRV-to-LRV distance is defined by three membership functions. Each function is expressed with Gaussian curves (Fig. 10).

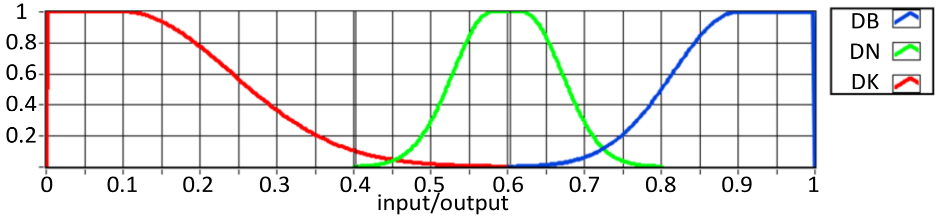

Fig. 10. Chart of the LRV-to-LRV distance function

The set is designated with capital "D" and includes the fuzzy functions of "safe distance" DB "normal distance" DN, and "collision distance" DK.

The differential speed between the trams is defined by three fuzzy functions (Fig. 11): "differential speed – trams move away" RO, "differential speed – constant LRV-to-LRV distance" RS, and "differential speed - trams approaching" RZ.

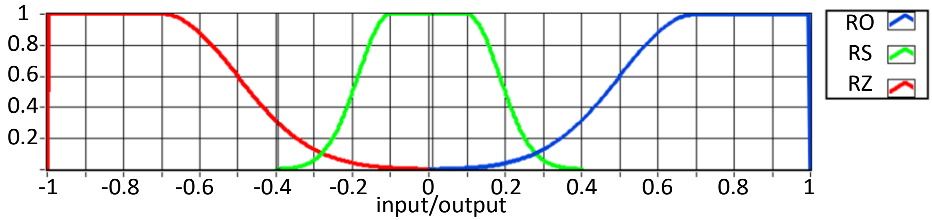

Fig. 11. Chart depicting the change in the differential speed of the LRVs

The last of the input parameters processed by the decision-assist system is the following tram speed, v_2. This parameter is expressed by five triangular functions (Fig. 12): "very low speed" V2_BM, "low speed" V2_M, "average speed" V2_S, "high speed" V2_D, "very high speed" V2_BD.

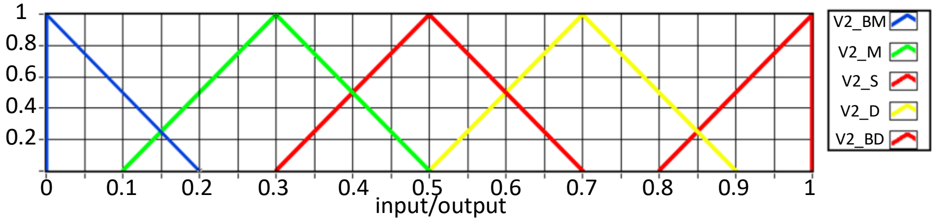

Fig. 12. Chart depicting the indication of global variables for the control of linear acceleration and angular velocity recording

The output value is determined with a fuzzy set called "Braking" (Fig. 13). It is a variable express by five Gaussian functions: "no hazard" H_BZ, "low caution" H_MU, "caution" – H_U, "extreme caution" H_SU, "hazard present" H_Z.

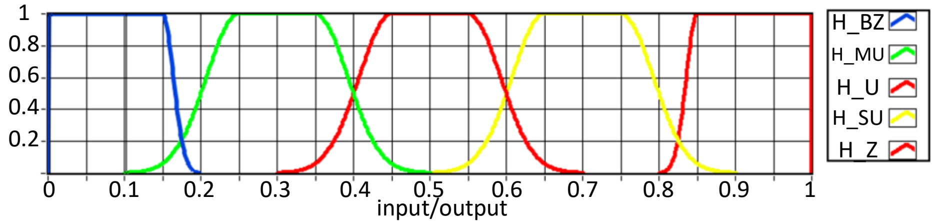

Fig. 13. Chart depicting the output variable "Braking"

Each decision is formulated by the expert system with 45 rules which define the relationships between the individual fuzzy sets. The output value is estimated with the method of surface centre determination.

The decision-assist system is implemented in an sbRIO – 9607 controller manufactured by National Instruments. The system passed preliminary testing, by which it was demonstrated that the expert system performed correctly. Fig. 14 and 15 show a result of the simulated operation of the decision-assist system. The analyses were run by modifying one of the input parameters and an assumption that the two remaining input parameters hold constant values. If the following tram speed, v2 is constant, the differential speed tells that the trams are approaching one another and the expert system's decision will be driven by the value of distance. If a small distance is detected, the expert system advises to brake the tram absolutely (the output value approaches 1) and when the maximum distance is reached, the tram driver is advised to remain cautious.

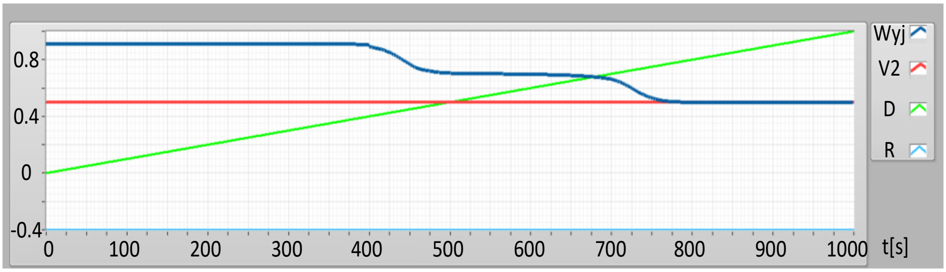

Fig. 14. Chart depicting the driver-assist inference system's feedback for the function related to varying LRV-to-LRV distance, D at a constant speed, V2 and a differential speed < 0 (the LRVs approach one another)

Another analysis (Fig. 15) was run at a constant speed of the following tram, a constant LRV-to-LRV distance, and a varying differential speed. Note that the level of hazard was reduced as the differential speed increased. A negative differential speed value meant that the trams were approaching one another; a positive differential speed value meant that the trams were moving apart. An increase of the differential speed value meant that the leading tram was accelerating while the following tram maintained a constant operating speed, which should significantly reduce the collision hazard (the output value was near to zero).

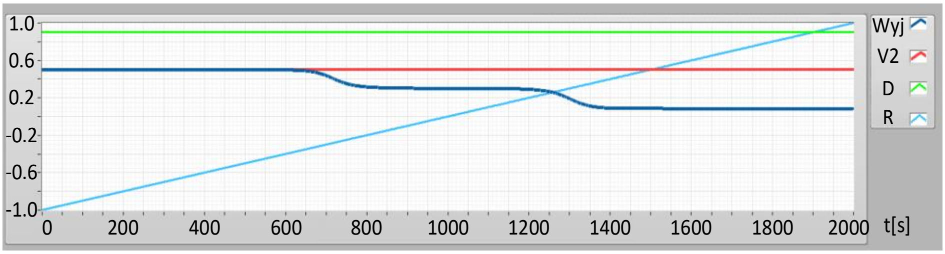

Fig. 15. Chart depicting the driver-assist inference system's feedback in the function of varying differential speed, R at a constant operating speed, V2 and a large LRV-to-LRV distance, D

4. CONCLUSIONS

This paper presents key components of the tram anti-collision system. The focus was on the video recognition system, VLC, HUD information display, and the expert system tasked with assisting the decision-making process of the driver. These are the key subsystems of the anti-collision system.

They are complemented by solutions based on systems designed to measure tram traffic (motion) parameters (the distance covered and the operating speed) and GPS navigation subsystems which support the process of positioning the tram along the tracks. The anti-collision system features an ArUco marker image processing system. Its task is to detect graphic markers which trigger the reset of the distance covered counter. The ArUco markers mounted in the tram's infrastructure (like tram stops) can be used to notify the tram anti-collision system that its host vehicle is at the beginning of a road section, triggering the distance covered counting. This solution is key to correct positioning of the tram on the track.

The ArUco marker optical recognition system allows determination of the distance from a marker on an LRV ahead of the host LRV. Another functionality of the system provides structural redundancy, which can be used to improve accuracy.

The tram anti-collision system components are interconnected by a CAN bus. The CAN bus and the modular system architecture allow configuration for the end-user. Moreover, the LRV anti-collision system can be installed in a modernized tram without changing the vehicle's structure.

Work is under way to verify the performance of the tram anti-collision system components under laboratory test conditions similar to operating conditions and under real-life conditions. There is also work being done to integrate the anti-collision system components over CAN bus.

FUNDING

The paper contains the results of the research work financed by the Polish National Centre of Research and Development, 2014-2020 Scientific Fund, Development Project no. POIR.04.01.02-00-0041/16.

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Projekt koncepcyjny systemu antykolizyjnego dla pojazdów szynowych

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Streszczenie. W artykule przedstawiono koncepcje systemu antykolizyjnego przeznaczonego dla pojazdów szynowych. Zadaniem systemu jest wypracowanie informacji wspomagającej motorniczego w podjęciu decyzji o rozpoczęcie procesu hamowania. System opary jest na wykorzystaniu informacji z wielu źródeł (układu wykrywania przeszkód, układu rozpoznania obrazowego, układu komunikacji świetlnej) i na podstawie algorytmu zaimplementowanego w systemie eksperckim, zobrazowaniu informacji dla motorniczego na wyświetlaczu przeziernym.
Słowa kluczowe: inżynieria mechaniczna, system antykolizyjny, układ wykrywania przeszkód, układ rozpoznania obrazowego, system ekspercki.