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Collision risk mitigating system for light rail vehicles(LRV)

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ABSTRACT

This piece is dedicated to the description of the development of collision risk mitigating system. The proposed concept of control system is designed to enhance safety of passengers, a driver and other people in vicinity of light rail vehicles (tramways). The requirements were fulfilled thanks to the application of lidar sensor and feature of vehicle positioning on the track map created basing on precise measurements with the use of satellite navigation system Real Time Kinematic. The map allows to eliminate errors of system operation and to enhance resistance to unfavorable ambient conditions, i.e. temperature or fog. The system calculates work braking distance for particular vehicle speed. In case of obstacle detection which is closer to vehicle than the calculated braking distance, the driver is informed about a collision risk with a buzzer and optical signalization. The system has already been implemented and tested.

1. INTRODUCTION

With the raise of traffic intensity in urban areas and more frequent interference of railways, roads and walkways the risk of collision with light rail vehicles with other types of vehicles and pedestrians has grown considerably [1]. Quickly growing automotive industry began to implement active anti-collision systems [2]. This direction became interesting also for the providers of railway transport services.

A good answer to growing market demand is the development of active mechatronic system that enhances driver's vigilance in emergency situations. Drivers who cover the same route every day are subject to routine behavior and problems with maintaining proper focus. The system informs them about potential danger with sound buzzer and optical signalization.

In the course of execution of anti-collision system project a following problem was encountered. How to predict the exact path of tram movement in dense urban area? The problem may seem easy to solve at first glance – after all tram moves on rail tracks. For human perception this is indeed easy, however when this data is to be interpreted by a computer the whole matter becomes much more complex.

2. METHOD

Utilizing the experience of automotive industry I analyzed automotive DAS systems (Drivers Assistance System). The basic difference between passenger cars and tramways is the average value of deceleration during braking which depends on the vehicle weight and wheel-track contact. In passenger cars in normal ambient conditions average deceleration is approximately 7.5 m/s^2 and in such case braking distance from velocity of 70 km/his shorter than 26m. Working braking distance of tramway (deceleration is approx.1.4 m/s^2) from the same speed is over 125 m which is 5 times more. In case of using emergency brake (average deceleration is 3.0 m/s^2) the distance is shortened to approx. 60 m [3]. This distance doesn't include driver's reaction time, slips or gradient of the tracks. Therefore the system should

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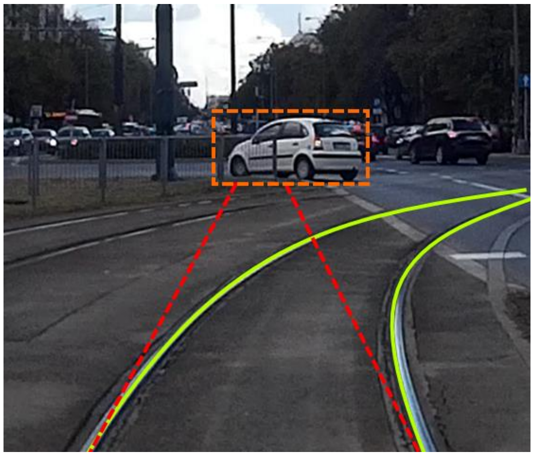
analyze the surrounding of the vehicle at the distance of minimum 150 m, including curves and intersections.

Available market offer consists of four systems equipped with stereoscopic cameras which recognize objects and estimate their distance. An example of a ride assistant for a tramway is DAS system created by Bombardier which has been undergoing tests in Frankfurt am Main since 2015 [4]. Vision systems are not resistant to unwanted ambient conditions like snow or rain. There is also a problem with measurements at distance greater than 150 m.

Basic functionality of Collision risk mitigating system (in Polish: System Ograniczający Ryzyko Kolizji [SORK])is analysis of surrounding environment using lidar (LIDAR stands for: Light Detection and Ranging). LIDARs work in the same manner as radars but they use light beam instead of microwaves.LIDAR scans the environment in front of the vehicle using laser beam. Its advantage over radars is basically the fact that LIDARs offer a good balance between short and long distance measurement device whereas in the case of radar systems two separate devices are required. Time of Flight method is utilized. It determines the time in which light pulse travels a particular distance in a particular medium. In LIDARs that we used lasers, pulses have the length of 3-20 ns. At this time industrial LIDAR sensors used in automotive industry can detect objects in the range of 300 meters.This solution is better than so-far stereoscopic cameras because of its far greater resistance to snowfall (tracks covered with snow), rainfall or fog interference. Tramways are commonly used in big cities with heavy traffic, a lot of pedestrians and developed track side infrastructure. To determine if there is no object on the collision course of tramway, LIDAR may not be enough.

One of the problems is to determine whether an object in front of the tram is actually on the collision course with the vehicle. In situation where in the curve area there are catenary pylons (Fig. 1) the utilization of LIDAR only will not provide necessary information.Similarly in situation where tracks go across a road such system would also receive insufficient information. In such cases in order to eliminate false alarms and operation errors it is necessary to determine the real course of tramway.

In order to avoid potential false alarm it is essential to reproduce layout of tracks and determine the route that the vehicle will follow. For that purpose we used a map of the track system which allows us to predict the movement of the vehicle.


a)


b)

Fig. 1. Trajectory of tramway movement a) crossing of the tracks with road, b) catenary pylons close to track curve

3. MAP OF THE TRACK SYSTEM

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The map of tracks system was developed with the use of GNSS (Global Navigation Satellite System) Leica Viva GS14 receiver. GNSS is a navigation system which was supposed to eliminate typical imperfections of GPS. We managed to assure this through multiplication of positioning information sources with the use of American positioning system Navstar, Russian GLONASS and European GAILEO. We are currently also working on integrating Chinese BeiDou [5]. These systems provide constant access to correction data and offer possibility to continuously monitor positioning data quality. The system features most advanced solutions from the field of real time kinematic (RTK) measurements [6]. Operation principle is basically the utilization of stationary reference receivers which transmit correction coordinates to antenna through GSM. RTK is a technology which allows to conduct precise measurements with the use of satellite navigation. It is a real-time calculations measurement method, without post-processing. In this case we decided to use transmission with one reference station. Moving receiver positions the coordinates based on its own antenna and on the signals from the reference station via radio transmission or GSM. Standard GPS receivers need access to four or more satellites to correctly measure the distance. GPS receiver determines position based on the distance from every satellite by analyzing relative phase displacements of unique code which is continuously sent by every satellite. The wave length is about 300 m which drastically limits the precision of distance to the satellite – measurement accuracy is +/- few meters (Tab. 1).

Tab. 1.Comparison of GPS and GPS RTK receiver [7]

	GPS	**GPS RTK**
Number of receivers	Single receiver	Receiver and reference receiver
Type of position	Absolute (geographical coordinates)	Relative (vector between receiver and reference station)
Precision of position (horizontal)	3-5m	1-5 cm
Precision of position (vertically)	12-15m	8-15 cm

The following items influence the precision of measurement [7]:

- Ephemeris error (gravity of the Sun, gravity of the Moon, solar wind),
- clock error (inaccuracy of the model pattern – 8, 64 – 17,28 ns),
- ionospheric lag (signal alteration in ionosphere layer),
- tropospheric lag (signal lag in tropospheric layer),
- signal reflection ,
- receiver error.

Thirty-two satellites in American GPS-NAVSTAR system orbit on mid Earth orbit and generate signal. They are located at distance of 20200 km from Earth surface. Between them and the surface at the altitude of 50 – 1000 km there is ionosphere which contains ionized particles of gases and plasma. This layer causes interference of GPS signal. RTK receivers measure the phase of low carrier wave which greatly improves precision (apart from standard measurement of GPS receiver). RTK receiver measures phase of carrier wave which modulates the code. The length of the carrier wave is approximately 19 cm. It makes it possible to greatly improve precision compared to the length of code wave which is 300 m. However there is a problem – because in this case the number of complete carrier waves between satellite and receivers is unknown.

In addition, RTK receivers are able to minimalize ionospheric lag because they use reference transmitters. They use algorithm to compare received data and displacements of the phase of carrier wave. It minimizes errors and thanks to bidirectional communication it is possible to eliminate interference.This is the main reason why we use at least two GPS RTK receivers.

For proper execution of RTK method it is crucial that both receivers contact the same way they do in the case of GPS standard with at least four common satellites – connection to greater amount of satellites provides better precision and dynamics. It is also important that both reference station and moving station have at least four common satellites [7].

4. SYSTEM

Numerous courses were made in order to acquire points and to register coordinates of the track system (Fig. 2). The courses were made during nighttime in order not to disturb regular passenger traffic. Velocity was strictly dependent on the height of buildings and density of infrastructure in vicinity of track system; it was also dependent on ambient conditions. The main problem related to the usage of this solution is the fact that the device was designed to low-speed attempts (it was designed for manual operation by geodesist traveling on foot) which doesn't allow to measure the route with speeds greater than 25 km/h. During the process of the creation of track system map the vehicle was able to achieve the speed of 25 km/h without loss of precision at the level of less than 15 mm. However in the case of loss of the precision of RTK it was necessary to stop the vehicle until resuming the required precision level. Approximately 260 km of routes were measured. On intersections, tram loops and tram depots where maneuvering was problematic we used cart with measuring antenna and the measurements where collected manually.

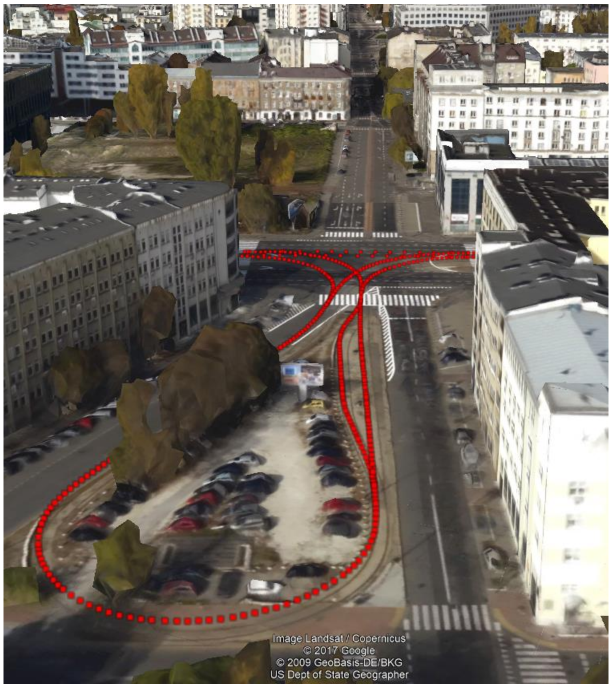


Fig. 2. Sokrates Starynkiewicz Square, Warsaw, Google Earth

When the map was created we developed an application (SORK – Collision risk mitigating system). Industrial computer receives data regarding position of GPS receiver (mounted on serial production vehicles) with positioning frequency of 10Hz (normally a lower frequency is used: 1-5Hz). The position is added to the map data. The application generates „virtual tunnel" in which a vehicle is moving. The tunnel is generated on the axis of a path created by measured points (Fig. 2). Its width equals the width of the vehicle's envelope. The length of the tunnel depends on the vehicle's velocity provided by master controller of the vehicle from speed sensors in bogie axles. The system calculates working braking distance (average deceleration of 1,2 m/s^2) for the given speed of fully loaded vehicle [8, 9].

Lidar analyses the environment around the vehicle and delivers information about obstacles in front of it. In the case when coordinates of objects are the same as coordinates of the estimated tunnel, the driver receives information about risk o collision via visual and optical signals (Fig. 3). Launching of a warning signal is recorded by the vehicle's event recording unit (Juridical Recorder Unit) which is a separate component that is not directly a part of the system. This solution enables data analysis in case of post-emergency situations.

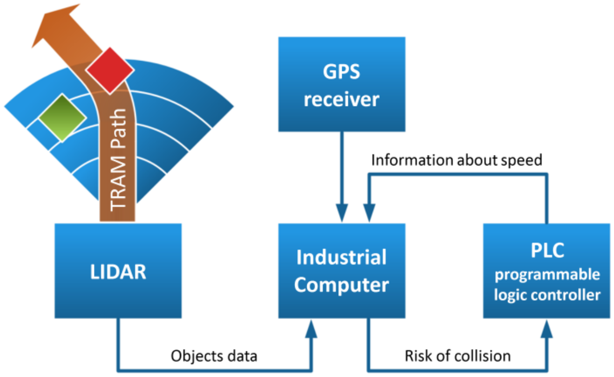


Fig. 3. SORK block diagram

Having assessed the danger, the driver can implement emergency braking which uses maximum power of electrohydraulic brake system and electromagnetic brakes (average deceleration of 3 m/s^2).

We also implemented algorithms that block the possibility to deactivate the system in case of GPS signal interference which use the approximated GPS data and add them to the track pathway.

False alerts caused by grass and branches that appear on the tracks were eliminated thanks to skipping objects smaller than 50cm.

Based on the studies of system behavior in the case when a tramway follows another tramway the system, using Lidar, measures the velocity of the leading vehicle. The system calculates emergency braking distance of the observed vehicle from the measured speed. In the next step the program calculates distance between two tramways that assures safe braking of the tramway equipped with SORK in a situation when the leading (observed) tram employs emergency braking. If the distance is not safe the driver receives information regarding collision risk and a need to make the distance between tramways longer.

Figure 4 depicts general algorithm of functioning of the collision risk mitigating system. The system reads data from Lidarand coordinates from GPS receiver. Then it assigns coordinates to the route and direction of movement (elimination of deviations). Section of the route is uploaded to the system. Working braking distance is calculated based on data regarding velocity of the vehicle. These calculations are base input to define the danger zone. In the next step identified objects are categorized into classes: big, medium, small and distortions (for example rain drops). Objects smaller than 50 cm are not considered at all. System analyses only objects which are in the danger zone and assesses their distance from the tramway. In case of objects which are closer to the tram than braking distance the system generates flag for the risk of collision. If the driver doesn't start braking the system generates warning of collision risk via acoustic and visual signal.

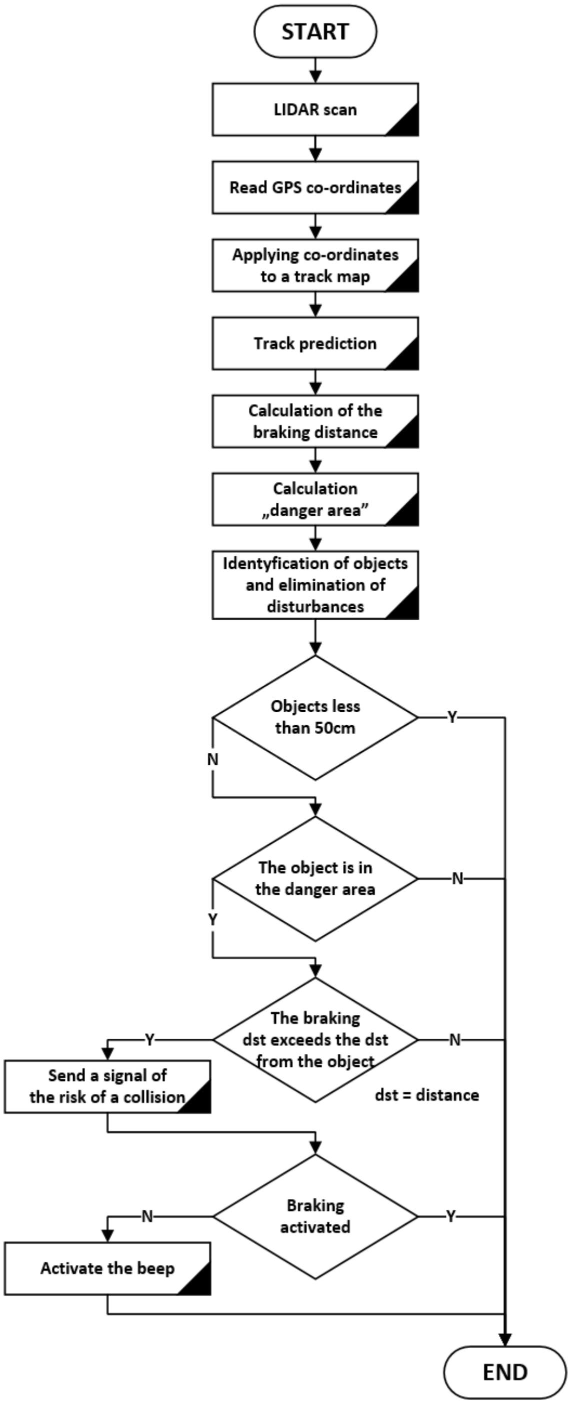


Figure 4Algorithm

The system analyses if the calculated work braking distance at given velocity is smaller than the distance from the obstacle detected by LIDAR. If the braking distance is greater, alarm is activated. Based on brake calculation data for brake system, the average vehicle deceleration is calculated (1). Initial vehicle speed is also considered together with equivalent deceleration of the vehicle and equivalent response time. The average vehicle deceleration is then calculated for 3 scopes of vehicle load (Tab. 2).

Tab. 2. Equivalent deceleration of vehicle for different load

Passanger load	Weight range	Equivalent deceleration of vehicle, a_{eg}
-	[kg]	[m/s^2]
empty vehicle	0 – 8 999	1,57
>50% load	9 000 – 11 999	1,52
>67% load	> 12 000	1,43

Equivalent response time of the brake system for service brake, t_{eg} = 0,26s.

$$a_s = \frac{va_{eg}}{v + 2a_{eg}t_{eg}} \qquad (1)$$

where:
a_s – average vehicle deceleration [m/s^2],
v – initial speed [m/s],
a_{eg} – equivalent deceleration of vehicle [m/s^2],
t_{eg} – equivalent response time [s].

The calculations were performed for particular speed thresholds. The results are presented in (Tab. 3).

Table 3. Service brake - Average vehicle deceleration

Initial Speed	Emptyvehicle	>50% load	>67% load
[km/h]	[m/s^2]		
10	1,21	1,18	1,13
20	1,37	1,33	1,26
30	**1,43***	1,39	1,31
40	1,46	1,42	1,34
50	1,48	1,44	1,36

*Required deceleration [3]: a_s> 1,4 m/s^2 for an empty vehicle.

Achieved stopping distance s is calculated based on average vehicle deceleration (2).

$$s = \frac{v^2}{2a_s} \qquad (2)$$

The calculations were performed for particular speed thresholds. The results are presented in (Tab. 4). Theoretical calculations meet requirements of standards [3] with regarding to average vehicle deceleration and vehicle braking distance on level, straight track at the speed v = 30 km/h.

Tab. 4. Service brake - Achieved stopping distance

Initial Speed	Emptyvehicle	>50% load	>67% load
[km/h]	[m]		
10	3,2	3,3	3,4
20	11,3	11,6	12,2
30	**24,3***	25,0	26,4
40	42,2	43,5	46,1
50	65,0	67,1	71,1

*Required brake distance [3]: s < 24,8m for an empty vehicle.

5. RESULTS

We conducted numerous tests evaluating behavior of the system in following situations:

- Objects on the track,
- Vehicles passing on straight section of tracks,
- Vehicles passing on curves,
- Following another vehicle.

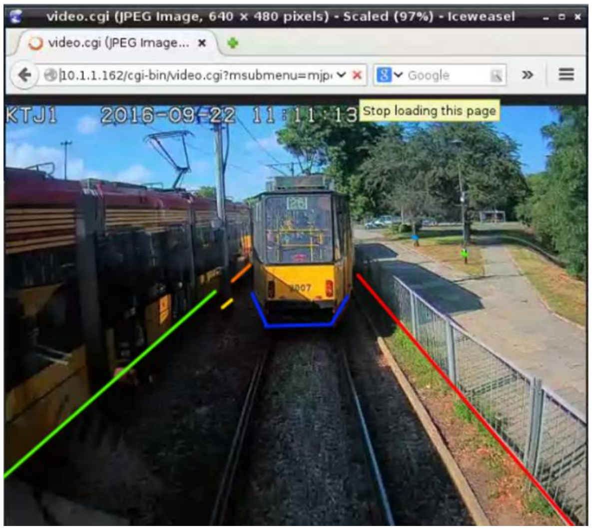


Fig. 5. Tram model 134N - route camera view

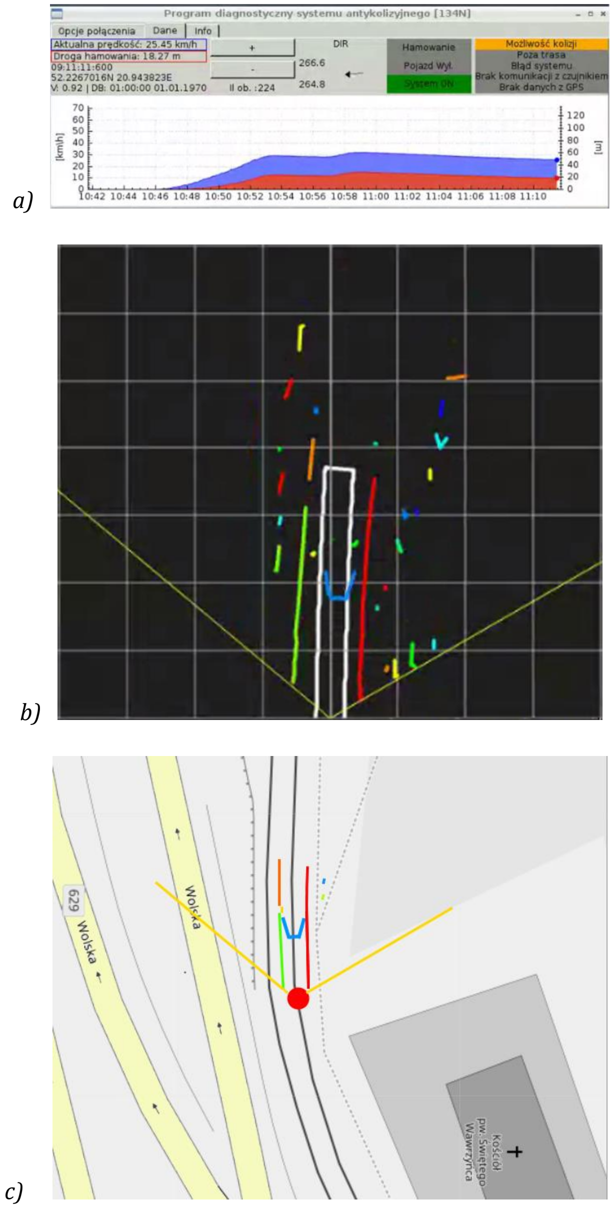
The most difficult test to conduct were tests of collision detection following another tramway (Fig. 5). Both leading vehicle and test vehicle were conducted by experienced instructors of tram operation. The aim of this function is to develop a habit among tram operators to keep proper distance from the vehicle ahead. Collision resulting from driving one tram into another are among the most frequent and most expensive collisions for fleet operators.

During the tests we used our own service program which demonstrates text and graphics regarding system operation on the computer screen. In the above example (Fig. 5) vehicle equipped with SORK is directly behind tramway ahead.

In the service program in Data tab (Fig. 6a)we can see the current vehicle speed of 25,45 km/h which is calculated based on speed signals from sensors mounted on vehicles axes connected to event registering device. Braking distance (2) calculated on this basis is 18,27m.

On the visualization that's created (Fig. 6b) the scope of Lidar work is clearly visible (yellow lines that create obtuse angle). White „rectangle" represents trajectory of vehicle motion and its height is the representation of braking distance. Pitch on the screen is 5x5 m per unit of grid. Blue lines represent the object on the collision course (tramway). As you can see it is closer than 10 m so its distance is almost two times smaller than calculated service braking distance. Therefore the risk of collision is reported.

In case of detection of moving objects like another tramway, in the moment of detection absolute speed of the object is calculated. Then system assumes that object may brake with deceleration of 3 m/s^2 and braking distance is calculated (2). Then the object is "repositioned" by the value of calculated braking distance on the path of the tramway. System once again verifies if it is in the danger zone. If this result is obtained in 5 measurements, an alarm is reported (Lidar operation frequency - 12.5Hz).



Aktualna prędkość: 25.45 km/h
Droga hamowania: 18.27 m
09:11:11:600
52.2267016N 20.943823E
V: 0.92 | DB: 01:00:00 01.01.1970
Il ob. :224

Fig. 6. SORK Diagnostics screen: a) vehicle parameters screen, b) vehicle braking trajectory, c) map with GPS coordinates

First tram had the same speed as the tested tramway (25,45 km/h). Braking distance (2) assuming deceleration of 3 m/s² is 8,32 m. Therefore when we add the distance from the vehicle 9 m and the braking distance of vehicles we get the result: 17,32m. This distance is smaller than the service braking distance calculated by the system. The risk of collision is reported.

In the visualization (Fig. 6b) we can also see additional objects that do not pose threat of collision. Green and orange line (on the left of vehicle trajectory) represent the tramway moving in the opposite direction. Red line represents the barriers that separate tracks from the sidewalk. They are also noted on other screens.

System is connected to GPS receiver which allows it to assign coordinates to locations where risk of collision is reported (Fig. 6c). It allows us to indicate most dangerous spots and helps us to identify places in which false alarms are issued due to infrastructure elements or plants in the envelope of the track system.

After the phase of testing, adjusting the sensibility of the system and series of supervised test rides, and accounting for parameters like slope and poor quality of infrastructure, possible exploitation wear, possibility of slippage due to atmospheric conditions, we used the safety coefficient and we lowered the value of average vehicle deceleration that was used for calculations (s) to 2 m/s² (Fig. 7).

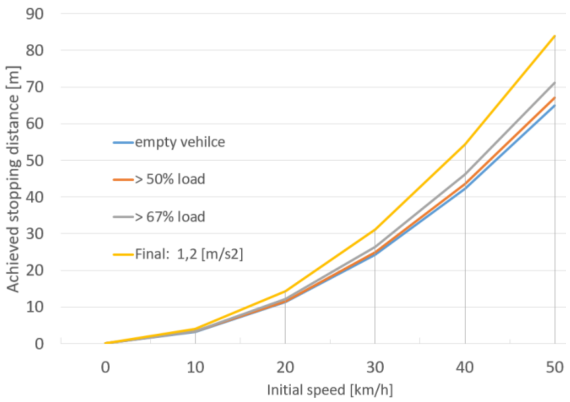


Fig. 7. braking distance graph depending on average vehicle deceleration

6. CONCLUSIONS

The system was implemented in serial production tramways and has been tested in regular operation.

It meets all given requirements and improves safety in urban conditions. Avoiding at least one collision justifies its implementation and makes further development meaningful.

At this moment we are conducting calibration works with the aim to improve system's reliability in the field of collision risk signaling irregularities. The system has potential of adding additional features like automatic activation of warning buzzer (solution equal to a horn in automobiles) in order to warn the surrounding of the tramway.

ACKNOWLEDGMENTS

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