*Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria*

# ODAS – An anti-collision assistance system for light rail vehicles and further development

Landri Fel a*, Christian Zinner b, Thomas Kadiofsky b, Wolfgang Pointner b, Johann Weichselbaum b, Clemens Reisner c

[a]*Bombardier Transportation Austria GmbH, Hermann Gebauer Strasse 5, 1210 Vienna, Austria*
[b]*AIT Austrian Institute of Technology GmbH, Donau-City-Strasse 1, 1220 Vienna, Austria*
[c]*Mission Embedded GmbH, Gutheil-Schoder-Gasse 8-12, 1100 Vienna, Austria*

**Abstract**

In the last three years, Bombardier Transportation and its partners have developed and brought to market ODAS (Obstacle Detection Assistance System), the world-wide first anti-collision system for light rail vehicles (LRV), which is homologated and commercially operated on tramway fleets. The motivation was a further safety increase in LRV operation by reducing the risk for collisions. Important milestones for the complex development and industrialization process are presented. The ODAS system architecture and its assistive operating principle are based on stereo vision as sensor input. Thus, the system is capable of deriving all information necessary for detecting obstacles in the driveway of the LRV and estimating a level for collision risk solely from images that are produced by three cameras mounted in the vehicle front. This makes the concept well suited for retro-fitting existing tramway fleets. Current investigations are targeting new functions and applications derived from the current ODAS technology such as cartography-based localization and automatic overspeed protection.

*Keywords:* collision avoidance; driver assistance; stereo vision; tramway; cartography; ODAS

* Corresponding author. Tel.: +43 1 25110-410; mob.: +43 664 859 51 94.
*E-mail address:* Landri.FEL@rail.bombardier.com

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### 1. Introduction

Due to the complexity of traffic in cities, and the resulting high level of attention and reactivity requested from the drivers, severe collision and derailment events involving tramways and city-trains may occur incidentally. These accidents generate enormous costs for the tramway operators and may lead to severe or even lethal injuries to the involved persons.

The frequency and severity of accidents involving tramways can be better illustrated by some figures:

- in Germany between 2012 and 2015, Destatis (2017): in average per year, 1082 accidents involving tramways leading to injure 1539 persons of which 39 were killed.
- in Switzerland in 2016, BFS (2016): 33 accidents involving tramways leading to injure 30 persons of which 3 were killed.
- French statistics about tramway accidents in STRMTG (2015) show around 2 persons killed per 10 million passengers. In 2014 with tramways operated in 28 French cities, 6 persons were killed and 31 seriously injured.
- During the first months of operation of a completely new tramway network in cities having no history with such public transport, the number of collision accidents can raise to dramatic levels. For example, in a large city in North Africa that started operating a fleet of 70 vehicles in 2013, Yabiladi (2013): 134 collisions killing 5 persons occurred during the first 10 months of operation.

The automotive sector is now demonstrating the efficiency of driver assistance systems in avoiding collisions and reducing the risk of accidents. However, such existing autonomous emergency braking (AEB) solutions are not directly applicable for trams because operation scenarios and vehicle dynamics differ significantly. Cars can usually brake with full intensity at up to -9 m/s² without endangering the own passengers, while tramway operation has to avoid injuries of falling passengers, thus, emergency braking intensity must be limited. This results in a much longer braking distance and range of the sensors used. **Fehler! Verweisquelle konnte nicht gefunden werden.** illustrates a comparison of automotive AEB test results with a tramway scenario in terms of deceleration curves plotted over the distance to the obstacle. While the best performing automotive AEB tested in Hulshoft et al. (2014) accomplishes a standstill from a speed of 50 km/h, many other systems provide a standstill from a speed of up to 30 km/h. The required reaction distances are then only 15 or 9 meters, respectively. In contrast to that, a tramway AEB maintaining a standstill from 35 km/h requires already a reaction distance of 28 meters. These much longer detection ranges in the tram scenario require an exact knowledge about the future trajectory of the rail vehicle, which is a quite demanding task. For the short reaction distances of car AEBs, the future trajectory is usually extrapolated from the cars' current steering angle. Therefore, using existing automotive AEB systems without major modifications would have a very limited effect on avoiding collisions with tramways and would also have to comply with regulatory specificities in the rail domain. In Gruber (2015) a way to demonstrate the safety of the tramway collision warning system is described and compared to similar concepts in the automotive sector.

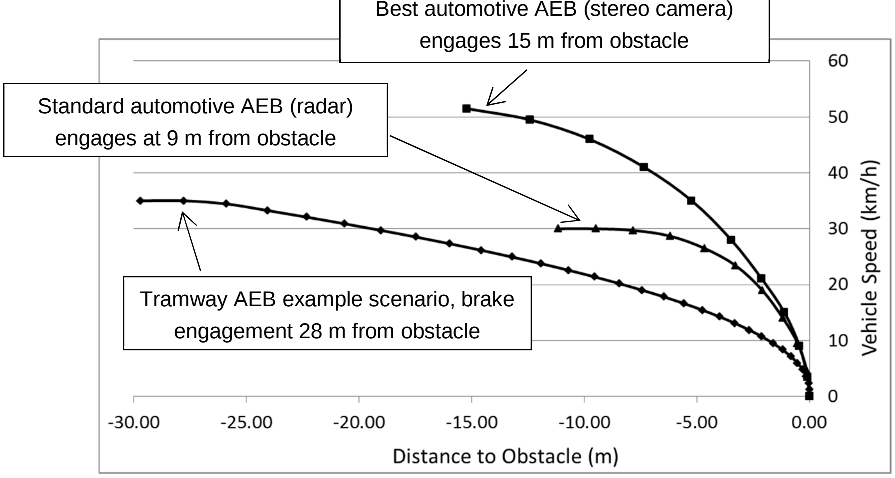


Figure 1: Deceleration curves and detection range comparison. Data from automotive systems taken from AEB test results published in Hulshof et al. (2013); Typical tram deceleration (operational breaks): -1.65 m/s²

The task becomes even more challenging when tram assistance systems like ODAS provide protection for vulnerable road users (pedestrians, cyclists, child buggies), which are usually much smaller than vehicles and have a widely varying appearance. This makes it harder to distinguish them from ubiquitous infrastructure elements such as masts, bollards, etc.

In the last three years, a team led by Bombardier Transportation (BT) has succeeded in developing and bringing to market ODAS (Obstacle Detection Assistance System) as an assistance system for drivers operating light rail vehicles. ODAS, as a commercial product, is one achievement of a long and intensive research effort started in 2005 by AIT Austrian Institute of Technology (AIT) in the field of computer vision and high performance image processing. High speed multi view 3D reconstruction technology has been permanently developed for a wide range of applications like medical scanners, robots and (semi-) autonomous industrial & and off-road vehicles as described in Rößler (2017). As of 2010, AIT started testing and evaluating its genuine 3D-vision technology in a railway-specific use case in the context of a cooperative national research project dealing with technology development for automated operation of a regional branch train operating on open tracks (see Gebauer et al. (2012) and Weichselbaum et al. (2013)).
In this and subsequent research projects, the scope for AIT was to further develop the 3D vision sensor technology for application on land vehicles like e.g. in (Kadiofsky et al. (2013), specifically in the optical and infra-red band ranges. The know-how built up during these projects constitutes a technological baseline of the ODAS system. In 2013, AIT and BT started a partnership for developing an obstacle detection system specifically dedicated to assist light rail vehicle (LRV) drivers. The principle of this partnership was, from the beginning, to question the real needs of the LRV operators and drivers and propose a turn-key solution addressing the very specific requirements of an LRV operating in an urban environment: guided path, sharp curves, relatively long braking distance, tracks inserted in mixed traffic streets, pedestrian zones, etc.
A development program on LRV vehicles has been run extensively and continuously in close cooperation with the Frankfurt LRV operator VGF since 2014. First operational trials and long term in-service evaluations have been run with 3 additional operators in Cologne, Berlin and Marseille with prototype installations.

In 2015, Mission Embedded (ME), part of FREQUENTIS group, has joined the development team and is now acting as a complete system supplier for the serial ODAS products.
In June 2015, the first worldwide authorization for operating in commercial operation an anti-collision system was granted to ODAS by the homologation authorities TAB in Frankfurt.
In 2016, a new set of serial components has been qualified for use on LRVs. The maintainability functions have been brought to a standard enabling easy calibration, diagnostic and corrective maintenance.
In February 2017, the two ODAS variants Step 1 and Step 2 have been granted a SIL 0 safety assessment by a qualified independent safety assessor.
In 2017, ODAS is under deployment on 74 vehicles of the VGF fleet in Frankfurt and a second European customer has been gained.

The subsequent sections of this paper are organized as follows. Section 2 presents the architecture of the ODAS system, while section 3 provides an overview of its main operation principles. The section 4 summarizes the capability and current performance of the ODAS system. Section 5 introduces some of the foreseen new developments and functions that may be derived from this technology.

## 2. ODAS system architecture

ODAS is an Obstacle Detection Assistance System based on stereo-cameras. It is assisting the driver by sending alarm signals or braking commands in case of a detected collision risk. The hardware of an ODAS system consists mainly of 5 components: a group of 3 digital cameras, a camera synchronization facility (SyncBox) and an ODAS controller.
The camera hardware, i.e., the sensor chips and optics, has been selected carefully during the design phase of ODAS. The main demands on the sensor chips result from the broad variety of difficult light conditions that have to be dealt with by the system, e.g. bright sun light with possible back light during day or only a little amount on ambient light combined with bright spotlights during night. Hence, a high linear dynamic range is an important requirement to reach similar performance to the human eyes. Furthermore, a high image resolution is necessary in order to achieve the required level of accuracy. Another important consideration is the focal length of the optics and the resulting field-of-view of the system. On the one hand, a narrow field of view is preferable in terms of accuracy, but on the other hand, a wide field of view is essential for being able to observe the tracks in

sharp turns. The group of 3 cameras is mounted most often behind the driver cabin windshield, in its upper part. The asymmetric setup with 3 cameras looking in the same direction allows for combining a small stereo baseline (0.25 m) for short range with a larger baseline (0.8 m) for long range depth estimation.
The camera images, which are the only sensor data input, are processed on the ODAS controller. The complex functions of the system are executed by innovative software that integrates mainly 4 different functions:

- Identification of the track position and trajectory
- Computation of the future dynamic envelope of the tramway in 3D space
- Detection of obstacles and estimation of the obstacles' position and movement relative to the tramway
- Computation of collision risk levels for each detected obstacle

The SyncBox is a second control unit, which is responsible for;

- Electrical supply of the 3 cameras and synchronization of the image acquisition
- Management of all input / output signals between ODAS, the driver and the other LRV systems
- Monitoring and reporting of ODAS system health status

Currently the ODAS system is available in two variants called *Step 1* and *Step 2*. This naming implies the degree to which ODAS is integrated into the vehicle and to which it can affect tramway operation.

- Step 1, which generates 2 successive (acoustic) alarm levels to the driver
- Step 2, which, in addition to the 2 successive alarm levels to the driver, can automatically trigger a moderate braking of the LRV that is overridable by the driver at any time

Figure 2 summarizes the ODAS architecture and the outputs of the 2 variants.

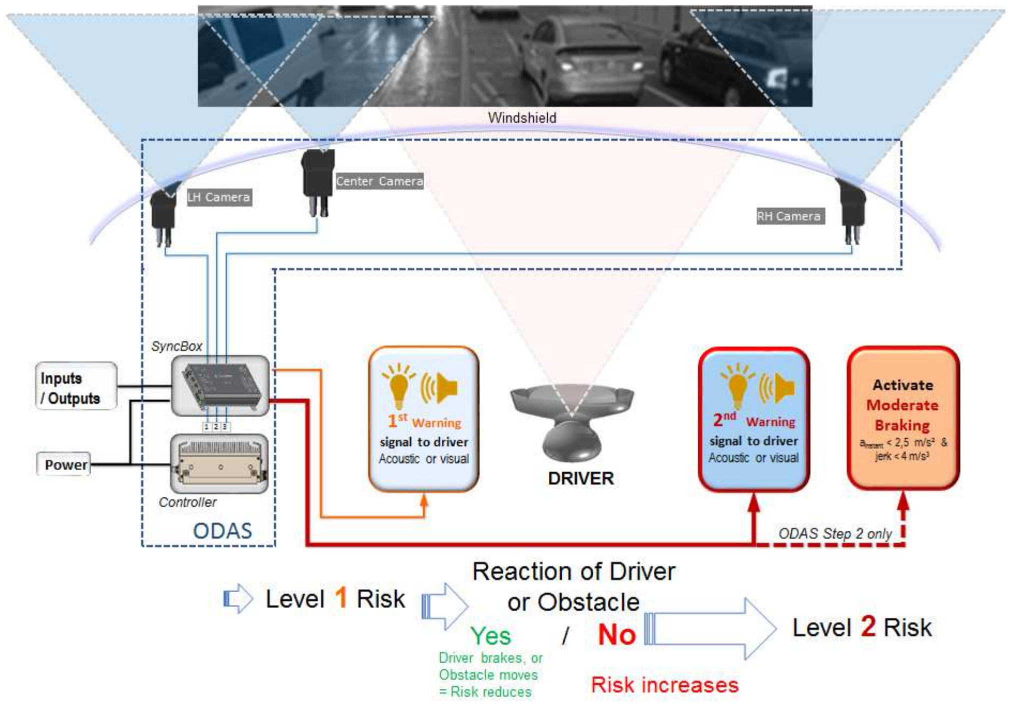


Figure 2: ODAS architecture

## 3. ODAS operating principles

This section gives an overview of the functional software components running on the ODAS controller, which process sensor data in order to reach a decision on whether warning or braking is necessary or not.

### *3.1. Stereo Vision*

Identifying the same point of an observed scene in two or more camera images captured from different points of view allows for computing the 3D position of this point relative to the cameras. This principle is employed in the AIT high speed stereo software engine called S³E, presented in Zinner et al. (2008) and Humenberger et al. (2009), which is able to compute depth information for each pixel in an image in real time on a common, not too demanding, hardware platform. The stereo matching process becomes challenging under certain conditions. For monotone and texture-less surfaces, a dense 3D reconstruction is hardly possible. However, usually at least the boundaries of such objects can be reconstructed. Other difficult situations are scenes with a very large intra-frame dynamic range, sun-glare that causes light scatter in the optical systems and rain droplets that might cause optical distortions. The stereo vision used in ODAS provides a good compromise between accuracy, robustness and computation speed. A specialty is the seamless combination of images of all three cameras to a single depth map, using a smaller baseline (0.25 m) for the near range and a longer baseline (0.8 m) for larger distances.

Advantages that influenced the choice of using stereo cameras for the 3D sensing are;

- A good lateral / angular resolution that enables a comparably fine discrimination of objects against the boundaries of the vehicles’ clearance gauge
- The image data can be re-used for tracks trajectory estimation and ego motion estimation and many possible future extensions
- Good coverage of several types of obstacles regardless of their material such as all kinds of vehicles, bicycles, persons, barriers, buffer stops, etc.

Maintaining an exact stereo camera calibration is important for stable operation. For the initial calibration, a procedure that guides a single maintenance person has been established to enable successful system calibration within a few minutes. Specific correction methods are able to monitor calibration quality during service and they also allow for automatic and transparent compensation of small changes of the relative camera orientations during rough operation conditions.

### *3.2. Ego-motion estimation*

One part of the collision risk estimation is computing virtual locations of possible collisions between the tramway and detected obstacles. Obviously, the vehicle speed is an important variable in these equations. Again, consecutive image pairs of a stereo system are employed for computing the 3D motion of the cameras by visual odometry as shown in Nister et al. (2014). Furthermore, the inertia of these high-mass vehicles together with a system model of the vehicle kinematics allow for further improving the resulting trajectory by a filtering process according to Kalman (1960).

### *3.3. Rail track detection*

Detecting the rail track in front of the vehicle is one of the major challenges of an AEB for tramways, since the track constitutes the future trajectory of the vehicle. ODAS is tackling this task by extracting the tracks also from consecutive images of one camera. These images are searched for discrete line segments, which are used to infer the continuous run of the two parallel rail curves with known offset (Figure 3). One challenge is that the visual appearance of the tracks is widely varying. Furthermore, in urban traffic environments, there is an almost ubiquitous presence of other linear structures such as lane markings, hatched areas on the street, edges of platforms and sidewalks which often run closely in parallel to one rail. Finally, one of the main difficulties is that one or even both of the rails might not be visible, e.g. due to occlusion by an obstacle. This is somehow paradox, because the track is of special interest in regions where obstacles are present. Hence, handling this paradox is a crucial step that had to be solved for ODAS. The current solution used in ODAS is the result of constant improvements over years and it is capable of estimating the track’s position and future tramway trajectory correctly in the vast majority of situations, including sharp turns with a radius lower than 20 meters.

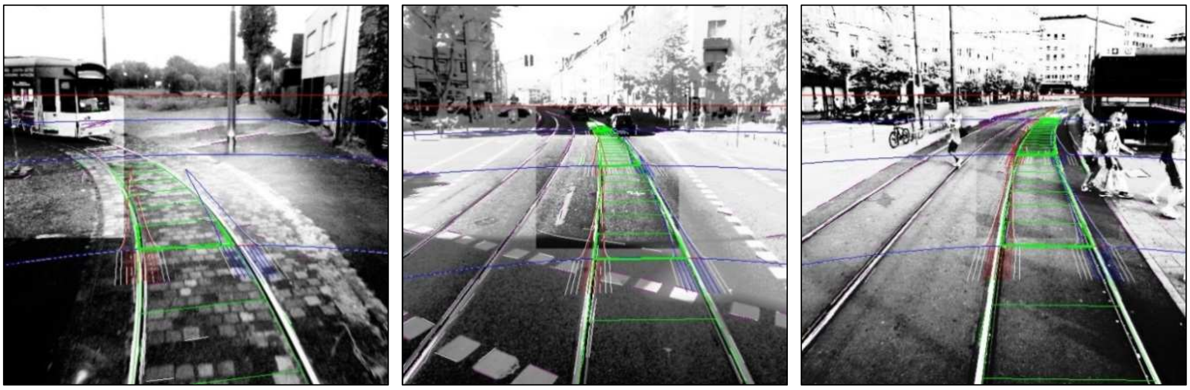

Figure 3: ODAS tracks recognition (visualisation of system-internals, not visible to the driver)

### *3.4. Obstacle detection and tracking*

Once the track has been identified in an intensity image, the combination with the respective dense 3D data from stereo vision yields a 3D curve in space. Together with the cross section of the vehicle, this curve spans the volume that is relevant for potential risks if obstacles intrude this. The 3D point cloud output of the stereo matching is segmented into objects of potential interest, which are within the swept path of the LRV or close to it. For arriving at a decision on whether to warn / brake or not, knowledge about the velocities of the objects is important, e.g. following a car, which is driving at the same speed, does not require a warning although the future drive path of the LRV is clearly violated. For this reason, the objects are tracked across consecutive images, which allows for deriving their relative velocities.

### *3.5. Summary of operating principle*

In a nutshell, ODAS is scanning the environment of an LRV by stereo vision, detecting the rails in camera images, combining both results to a 3D future trajectory, which is searched for potential obstacles, which are tracked for computing their velocities. In addition, the LRV's motion is computed by visual odometry. Finally, the three variables vehicle speed, distance to an obstacle and obstacle's velocity are used for computing the time to collision and the required deceleration for avoiding this collision. If the required deceleration rises above a critical value, a warning or a braking command will be triggered. The whole process is illustrated in Figure 4.

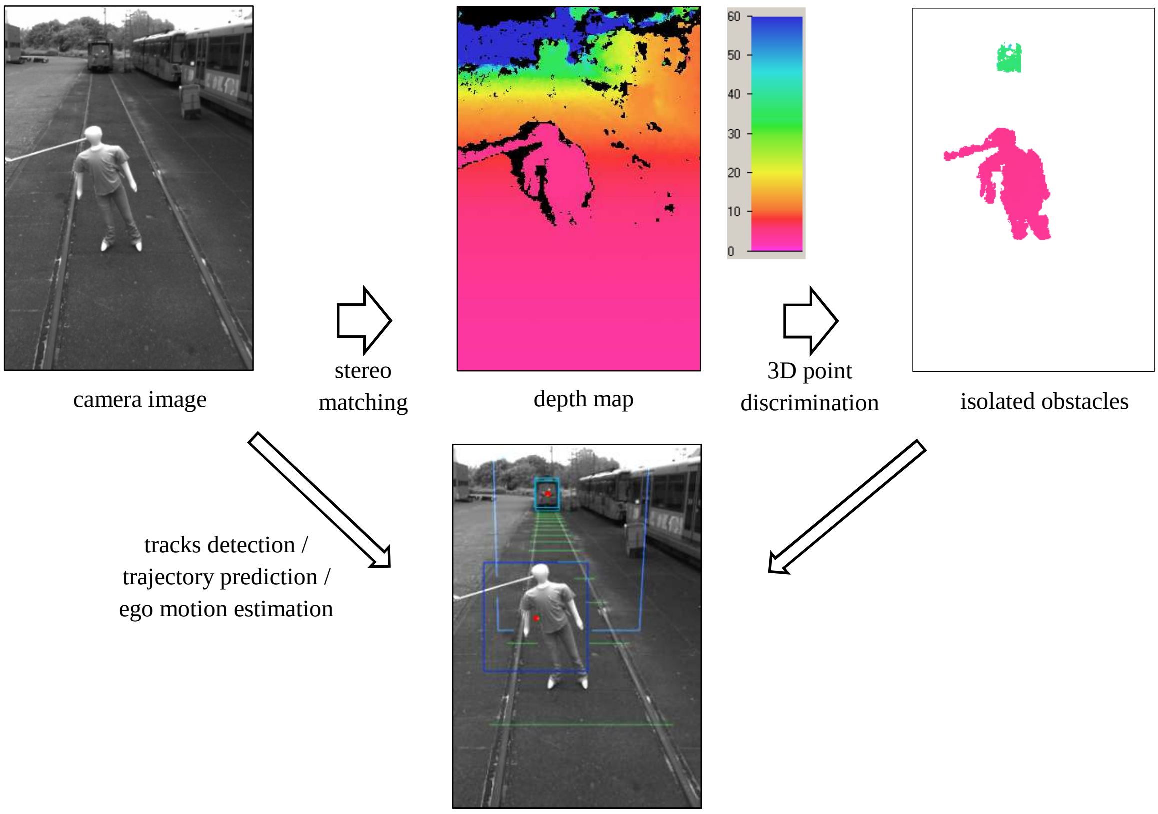


Figure 4: ODAS situation analysis process

## 4. ODAS capability & current performance

The ODAS system's performance and limitations in terms of visibility are similar to that of the driver's eyes. It works effectively during day, night, under rain and snow, provided that the luminosity and visibility conditions

are acceptable. ODAS detects virtually any kind of obstacles, that would pose a potential tramway operating hazard, that one can find in a city: pedestrians, bicycles, other vehicles, etc.
ODAS is a purely assistive system to the driver. The driver remains fully responsible for identifying and minimizing the risks of a collision. The driver can at any time inhibit the ODAS alarms and overrule any automatic moderate braking order.

Operational experience shows that first level warnings occur from time to time on a regular basis during normal operation, and these warnings are correct behavior of ODAS because of the "cautious" characteristics of the warning level parametrization (long observation range, moderate vehicle deceleration assumed, effective sensitivity even close to the borders of the clearance gauge). This is simply because other road users often do not consider the tramway driving dynamics correctly, e.g. passengers crossing the tracks closely on front of the approaching tram or overtaking cars changing lanes just in front of the driving tram. Due to the additional reaction time that ODAS considers for the driver for a timely manual braking after a warning, a driver that brakes on the spot before an obstacle can also provoke a warning from ODAS. Thus, the nature of such an assistance system in the tramway operational case is more interactive compared to automotive systems that are designed to only react in an absolute emergency situation, often when a collision is no longer avoidable.

There is a simple explanation for this different "philosophy": The speed envelope of normal inner-city car driving does by far not exploit the maximum braking intensities and deceleration levels (like racing drivers would do). In case of emergency, on full engagements of the brakes, an automotive AEB can utilize a reserve of an approx. 3 to 4 times more intense deceleration than normally used, thus there is a distinct difference between "normal" and "emergency" driving situations. This is in hard contrast to tramways, where maximum operational deceleration is regularly in use. Thus, an AEB for tramways will by nature be more interactive to the driver.

The feedback gained from dedicated automatic detection analysis tools and the drivers themselves over 3 years and thousands of accumulated kilometres shows that:

- There is no indication that a significant amount of false negatives (FN) occurred, which means that the overwhelming majority of real obstacles presenting collision risks have been detected.
- The occurrence of false positives (FP), where ODAS detects obstacles that do not present real collision risk, is occasionally still too high. The FP rate (FPR = FP/ (FP+TP)) is often above the empirically found "comfort" limit for FP to 10 % of total of detections.
- We have some indication that no spurious detections at all (FP rate of 0) is not good because the system would lose its "interactive" character. This can lead to a significant drop in driver attention and concentration because the driver will soon rely too much on the system and its capability of timely braking for any kind of obstacle.
- The true positive (TP) detections help the driver in focusing his/her attention to the driving situation.

## 5. Further developments & possible ODAS derivatives

### *5.1. Development strategy*

Bombardier Transportation's strategy is to develop solutions bringing an increased degree of automation into the various railway applications: light rail vehicle, but also locomotive, passenger train, automated people mover APM and metro. ODAS, as a starting base, and its further development has been identified as one key element in this strategy.

The current objectives set by Bombardier Transportation for the developments based on ODAS are:

- Further reduction of the false positive occurrences (less spurious detections)
- Increase the effective range of the obstacle detection for new applications (locomotive, metro)
- Reach the safety level required for triggering automatic emergency braking AEB in a tramway

### *5.2. Improving ODAS performance*

The reduction of the false positive rate down to a level that is perceived as "comfortable and useful" by the drivers is the main challenge we currently address. Most of the false positive detections can be assigned to one of the following three categories of driving situations:

- Transition from straight tracks into curves with small radii where the accuracy of the track detection is critical. A challenging factor is that the LRV approaches from the straight track towards the curve at high speed, thus the transition curve has to be recognized exactly over a large distance.
- Track switches where reliably predicting the future trajectory of the tramway is extremely difficult with optical data only.
- Degraded visibility conditions, for example a combination of night and rain.

In ongoing research projects, new methods based on on-board cartography and precise localization of the vehicle are investigated. First, we think that the combination of optical rail recognition, cartography and localization has high potential for improving the detection of the track in front of the LRV. Currently, the length of the visually detected track might be limited due to e.g. occlusions by objects or low image contrast caused by bad light conditions. This alternative approach would be more robust to these external influences and therefore the track geometry from the cartography database can be used to extend the warning distance up to the visual range of the camera system. Figure 5 shows an exemplary section of such a cartography database as well as track data projected onto a camera image. At the moment, investigations are running on test vehicles to assess the level of benefit that such a cartography process can bring when combined with the optical tracks detection process.

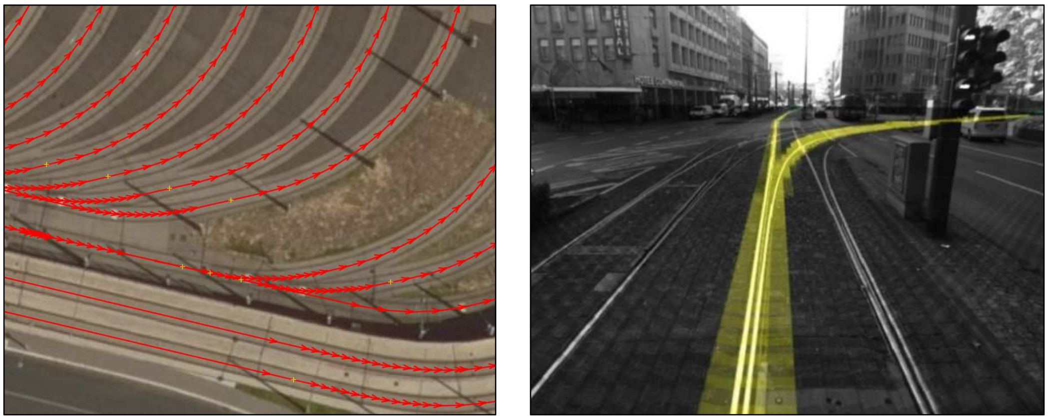

Figure 5: (left) cartography database; (right) database information of left rail augmented onto camera image

In the course of these research projects, a set of additional sensors will also be evaluated with regard to their potential to improve the exact real-time localization of the vehicle on the network. This set includes typical sensors employed for localization tasks, such as:

- Wheel odometry
- Inertial reference
- Optical / magnetic reference points
- GNSS, etc.

Furthermore, additional information available on-board the tramway about the current driven route might be used to resolve the ambiguities at track switches.

*5.3. Developing new functions*

Using the real-time localization of the tramway on the on-board map, we see the potential to reduce another type of risks seen in tramway operation: the risk of derailments caused by too high speed in curves or over track switches. An additional assistance function might be triggering warnings, if a driver approaches such sections too fast. The development of such a function is on-going in the frame of a research program called COMPAS (Collision & Overspeed Monitoring & Prevention Assistance System) managed by AIT in close cooperation with ME and BT.

*5.4. Potential new application fields*

The rapid progress made in developing ODAS for tramways shows the potential for adapting this technology to other types of railway vehicles like trains and metros. For these new application fields, the technical requirements will differ: longer detection ranges, higher speeds, larger curve radii, higher automation levels, more complex interface to the vehicle and to its surrounding traffic control and signaling systems etc. Thus, the obstacle detection components will have to be adapted, complemented and, quite probably, the system architecture will be different at the end.

## 6. Conclusion

In this paper, we present ODAS, which is an obstacle detection assistance system for tramways. We point out that ODAS is a pure assistance system available in the variety of Step 1 (triggering warnings only) and Step 2 (additional automatic moderate braking if warnings are not overridden by the driver). Specific differences between the tramway use-case and existing automotive AEBs are discussed. Requirements that result from these special operational conditions lead to the described ODAS concept and system architecture based on a sensor setup consisting of three cameras arranged in a stereo vision systems. The decision-making process on whether to warn the driver or not is based on the continuous observation of a defined volume in front of the tramway.
ODAS is intended to offer a sound solution for reducing the risk of collisions for new and existing light rail vehicles. Hence, this new technology is an important milestone for the LRV safety and it benefits both operators and other road users. ODAS is still undergoing a development process for enabling new functions and widening its field of application to other railway vehicles, e.g. in future work, we are addressing the problem of automatic overspeed protection in order to further increase LRV safety by reducing the risk of derailments.

## 7. Acknowledgements

We acknowledge the friendly support that we receive from various European tramway operators throughout the development of ODAS. Special thanks go to Verkehrsgesellschaft Frankfurt (VGF), regarding the R&D cooperation within the COMPAS research project.
A part of the work that led to this publication was funded by the "Mobility of the Future"-program of the Austrian Ministry for Transport, Innovation and Technology (BMVIT)

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