Anti-Collision Systems in Tunnelling: some Preliminary Tests Outcome on Effectiveness and OS&H in a System Quality Approach

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ABSTRACT: Underground works are generally characterised by the presence of narrow operating spaces, high concentrations of high-power equipment, use of iterative work cycles and haste in the excavation phases. These characteristics can cause interferences with a negative impact on production efficiency and can cause accidents and harmful pollution. As shown by the statistics on work-related accidents, one of the main causes of accidents is related to collisions between vehicles or between vehicles/pedestrians or structural elements.

From the design phase, the use of the functional volumes method, together with representation techniques (e.g., Gantt, PERT, Time-location diagram) is a valuable aid in planning operations, within a Prevention through Design approach. In the construction phase, the technological innovation of the anti-collision systems currently available is important for risk-reduction.

Eight types of systems were analysed: radar, radio frequency (RFID/RF), ultrasound, Bluetooth beacon, video cameras, infra-red cameras/rays, GPS and laser; also considering two "zero" systems, that are checking of the rear-view mirrors by the driver and the leaky feeder-based communication systems.

This paper discusses the results of the introduction of some anti-collision systems at TELT construction sites, in terms of system efficiency and quality, and OS&H improvements.

KEYWORDS: Tunnelling, Anti-collision systems, Tunnel construction safety, Underground equipment, OS&H

1. INTRODUCTION

Tunnelling and underground works present known criticalities that can increase the risk of interference between vehicles and pedestrians, impacting production effectiveness and quality and giving rise to work-related accidents [1].

During the transportation phases (e.g., for mucking, supplies, tunnel crews, etc.), these criticalities are increased, and serious safety problems can ensue, mainly due to poor visibility and blind spots around large vehicles and equipment [2, 3].

The 92/57/EEC Directive - temporary or mobile construction sites [4] includes in the general principles of prevention *to plan the various items or stages of work, which are to take place simultaneously*. A Prevention Through Design and Total Quality Management approach to tunnelling activities [5, 6] should cover materials and personnel transportation, in terms of preliminary optimisation of the system and feasibility analysis of physical segregation of pedestrian and vehicle areas (barriers or different levels), to eliminate or minimise the risk of overlapping of operating functional volumes of the various entities (workers and equipment) present in the underground [7, 8, 9].

In practice, however, the physical segregation, possible in some underground areas, cannot be generalised, in spite of the improvements in mechanisation and automation of many tunnelling phases, in particular at the face if D&B (Drill and Blast) excavation is used.

A specific Risk Assessment and Management [10] for every special tunnelling situation is needed, as the potential for vehicle and pedestrian collisions can vary depending on the adopted tunnelling techniques and technologies. This is confirmed by the large number of boundary parameters that must be considered and making it impossible to provide general elements of comparison in terms of OS&H (Occupational Safety and Health), in particular between the different tunnel driving techniques [11]. All the same, as stated in a semi-quantitative and comparative study by Tender et al. [12], D&B excavation is considered less safe than Tunnel Boring Machine (TBM) excavation, but in both cases the number of run-overs and accidents related to mobile equipment is still not tolerable.

As confirmed from international databases (e.g., Department of Labor DOL OSHA [13], Safe Work Australia [14] and JISHA - Japan Safety and Health Association [15]), one of the main causes of accidents and fatalities is related to collisions between vehicles and vehicles or mobile equipment/pedestrians or structural elements (as shown in Figures 1, 2 and 3).

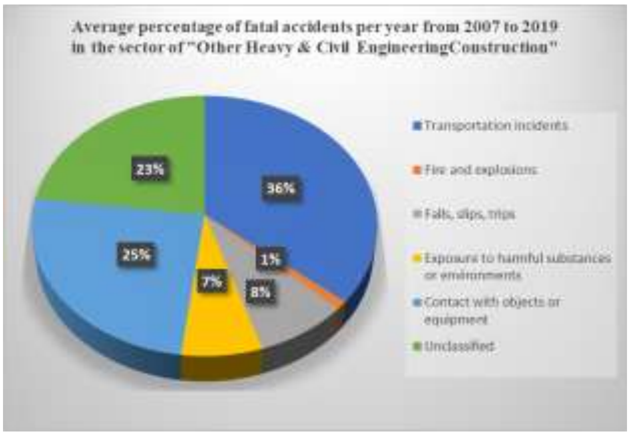

Figure 1: accident statistics from DOL OSHA in *"Other Heavy and Civil Engineering Construction"* (which includes tunnel construction) classified by event or exposure.

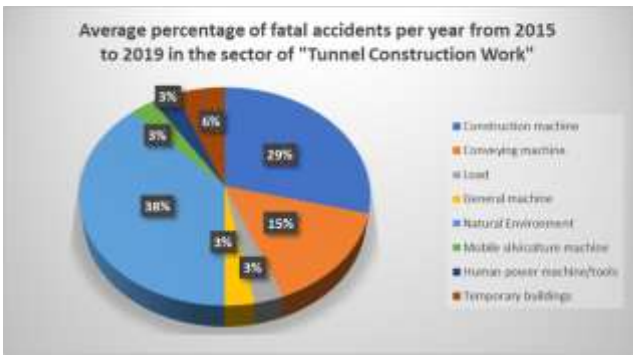

Figure 2: accident statistics from JISHA in *"Tunnel Construction Work"* classified by event or exposure.

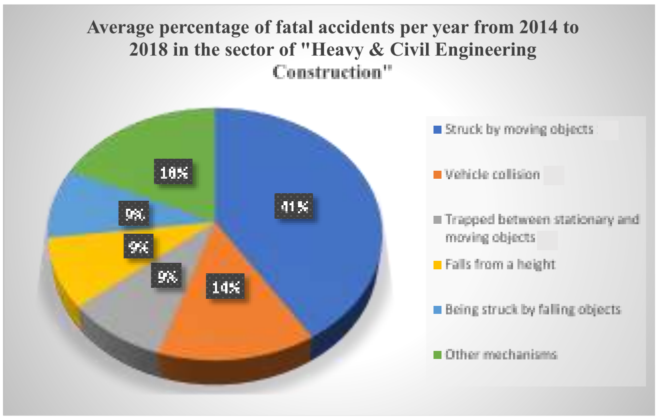

Figure 3: accident statistics from Safe Work Australia in *"Other Heavy and Civil Engineering Construction"* (which includes tunnel construction) classified by event or exposure.

With reference to tunnel excavation activities, and as a further confirmation of the critical nature of shared space, a number of accidents and fatalities related to transport and machinery still occur. As an example, the excavation of Alptransit tunnels (Switzerland) involved 8 fatalities, between 2001 and 2005, associated with transportation [16]. In [17], data from the Portuguese Government Office for Strategy and Planning and from project owners and contractors of tunnelling works show that, from 2012 to 2015, 14 to 32% of accidents involved machinery or vehicles (mainly trucks for muck transport, loader shovels and conveyor belts). More recently, in 2021, two major accidents due to the same causes occurred at the Terzo Valico high-speed railway tunnel construction site (Italy), [18].

It must be strongly underlined that, even though the Italian accidents database (INAIL - National Institute for Insurance against Accidents at Work [19]) records a limited number of events, due to the small number of Italian underground operations, the problem is not negligible, and worthy of preventive efforts.

Moreover, accidents caused by interference involve significant costs due to the resulting stoppages in the tunnelling operations [20].

Hence, it becomes very important to investigate the possibility of introducing innovative techniques and technologies currently available to reduce the occurrences and consequences of overlapping functional volumes, in accordance with the 92/57 EEC Directive (which highlights the importance of coordination of the organisational aspects to manage the risk of interference).

This paper proposes some questionnaires and a discussion, based on a review of the techniques and technologies used in anti-collision systems in tunnelling operations, of the efficiency of anti-collision systems in terms of worker safety and health.

Moreover, the results of the introduction of some anti-collision systems at TELT - (Tunnel Euralpine Lyon Turin, under construction as a part of the Trans-European high-speed rail network, Fig.4) construction sites, are examined in terms of system efficiency, quality, and OS&H improvements.

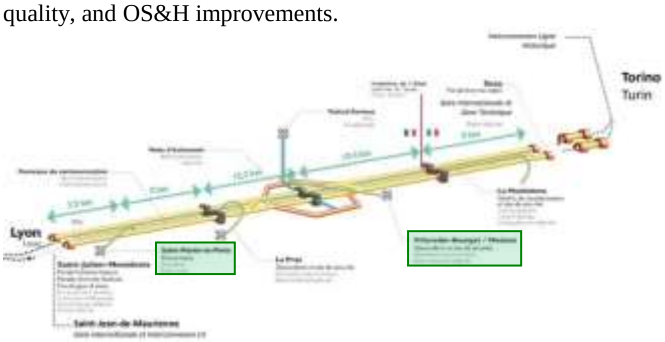

Figure 4: Lyon-Turin high velocity railway project, with indication of TELT sites involved in this study (in green boxes).

2. MATERIALS AND METHODS

In the previous study [2] eight types of technologies used in state-of-the-art anti-collision systems were identified. These technologies are: Radar, Radio Frequency Identification (RFID), Ultrasound, Bluetooth beacons, Video Cameras, Thermal Cameras/Infrared Rays, Laser and GPS – Global Positioning System (although currently the latter cannot be used effectively underground, but may be useful in surface yards). Table 1 summarises the main characteristics of the systems identified.

Moreover, two "basic" conditions are specified, which are the constant attention of workers, and of the equipment operators, including the checking of rear-view mirrors when operating in reverse; and leaky feeders [21], an effective communication system between equipment and personnel along the tunnel and between underground and surface, to facilitate their location.

Table 1: results summary of the investigations developed from [2].

1. Radar
❑ *Radar is a line-of-sight technology (no detection of object around the corners);* ❑ *Millimetre and microwave radar signals can penetrate dust, smoke, rain and fog;* ❑ *No need of wearable components for workers;* ❑ *High number of false alarms can make the use of radar in underground environments problematic: it cannot distinguish people from other objects;* ❑ *Position of radar unit can influence the detection efficiency.*
2. RFID (Radio Frequencies Identification)
❑ *Wearable components (tag/badge) are needed to measure distance, through signal strength;* ❑ *High frequencies allow longer distances (max 100 m) compared to low frequencies (max 30 m), but the latter can better penetrate large obstacles;* ❑ *Low number of false alarms. RFID can simultaneously detect multiple obstacles;* ❑ *Detection can be influenced by physical orientation of workers or by interfering frequencies (from other equipment).*
3. Ultrasound
❑ *Ultrasound is a line-of-sight technology and cannot recognise the nature of obstacles;* ❑ *Short range of detection (max 8 m).* ❑ *Minimum infrastructure and no wearable components needed.* ❑ *Environmental factors, size and distance of obstacles can affect detection. High frequencies from other equipment can interfere.*
4. LASER/LIDAR
❑ *LASER is a line-of-sight technology;* ❑ *Laser scans are planar (above or below the scanning plane, the obstacle is not detected).* ❑ *The real nature of obstacles cannot be recognised;* ❑ *Accurate and quick distance measurement (max 50-80 m) without interference;* ❑ *Environmental factors (e.g., dust, smoke) and target features (e.g., reflectivity) can affect detection;*
5. Video-cameras
❑ *Video-camera is a line-of-sight technology;* ❑ *Video-cameras use visible light imaging;* ❑ *Video-cameras can be complementary to other technologies, and distinguish obstacle type in real time;* ❑ *No signal interferences are possible;* ❑ *The range of vision (max 150 m) can be affected from environmental factors (mainly light conditions, dust, etc.).*

6.	Thermal cameras – Infrared Rays

- *Thermal camera is a line-of-sight technology;*
- *Promising use in underground settings since it does not use visible light (can produce crisp images in complete darkness);*
- *Provides information on the nature and exact position of obstacles, with long detection range (max 100 m);*
- *Environmental factors don't substantially affect detection;*
- *In very hot environment, the system is less effective.*

7.	Bluetooth Beacons

- *External components needed (beacons);*
- *Short detection range (max 10-20 m);*
- *Minimum infrastructures required (e.g., smartphone);*
- *Low number of false alarms;*
- *Direction and position of receivers condition the detection;*
- *High frequencies from electrical devices and installations can interfere.*

8.	Global Positioning System (GPS)

- *The dependence of this system on satellite signals prevents its use in underground environments (GPS is commonly used for surface operations). Special fittings can bypass the problem;*
- *Requires all personnel and vehicles to be equipped with GPS signal receivers as well as a radio for communication in real time with nearby equipment;*
- *Environmental conditions do not affect the detection.*

This selection was derived from an extended literature search performed according to PRISMA statements [22].

Additionally, for each identified technology, the operating principles, advantages and constraints relative to use in underground environments, and costs, were discussed in [2].

This paper, a development of the above-mentioned work, focuses on the evaluation of the practical effectiveness of the considered anti-collision systems when used in tunnelling operations, and discusses their possible future improvements.

In this study the anti-collision systems used at the TELT construction sites of Saint Martin La Porte and Villarodin-Bourget/Modane, were taken into account as practical cases.

In particular, to obtain some direct information of the in-field effectiveness and user friendliness of the various anti-collision systems, several questionnaires for equipment operators were developed, based on the type of anti-collision technologies with which the equipment used at the Saint Martin La Porte and Villarodin-Bourget/Modane TELT construction sites is equipped (see Fig 4).

The questions listed in the questionnaires were developed taking into account the results of the previous study [2].

The applicability of these questionnaires was evaluated by experts in tunnel construction.

3 RESULTS AND DISCUSSION

Figures 5 and 6 show the β release of the questionnaires for equipment operators.

The questionnaire in Fig. 5 refers to equipment fitted with RFID systems, while the questionnaire in Fig. 6 refers to vehicles/equipment fitted with video-camera systems.

In the questionnaire of Fig. 5 (RFID system), nine questions were selected, according to the results in [2]:

question 1: aimed to evaluate whether the new system imposes changes in the equipment operation approach: the introduction of a new technology can require an adjustment period, according to the level of complexity of the system, and to the conditions of the operating areas;

questions 2, 3: to collect information on the frequency of warnings from the system, and on the frequency of false alarms. The system may give false alarms since in underground environments there is potentially interfering noise generated by the high-power machines employed, and a number of structural elements which can influence the system's response, misidentifying objects that do not represent a real danger or disregarding real criticalities;

questions 4, 5: to investigate, from the operator's experience, where the system can automatically prevent potential collisions: the system initially warns the operator, and, if necessary, intervenes on the equipment's control/braking systems. It is important to know whether the early warning starts within sufficient time and distances, or whether it would be preferable to extend the range of the system, leaving the final decision to the operator;

question 6: RFID is not a line-of-sight technology: thus, according to its operating principle, it can detect identification tags also around corners at tunnel intersections. The question will provide direct feedback concerning the system's ability to detect personnel in the special use situation;

question 7: personnel and other equipment must be fitted with identification tags to allow detection by the system. Since in the underground environment the spaces are narrow and there may be a high concentration of personnel and/or machinery in the same area, the system should be able to effectively detect multiple tags to guarantee a high level of safety performance (e.g., in proximity of the face or along the tunnel in case of auxiliary excavation or fitting operations);

question 8: RFID can provide information on the proximity of a detected tag. The answer to question 8 can provide feedback on the effectiveness of the information given by the system to the operator, e.g., spatial position and distance of the tag from the moving equipment;

question 9: Underground, environmental conditions such as dust, smoke, mist, humidity, noise and vibrations, etc., can affect the system's detection capabilities (e.g., increasing the wear of system components). This this results in unexpected system faults, a lower-than-expected Mean Time Between Failures [23], reduced overall efficiency of the operation and economic losses.

The questionnaire in Fig. 6 (video-camera systems) introduces seven questions, selected, in this case also, according to the results in [2].

question 1: similarly to RFID systems, the question is aimed to evaluate whether the new system imposes changes in the equipment operating approach;

question 2: The operator must observe the monitor, to see what is happening around the machine (the system is not designed to directly intervene to prevent accidents);

question 3: To collect information based on direct operator experience on real cases where these systems have been instrumental in avoiding a potential collision.

questions 4, 5: distance of vision for camera systems is strictly linked to environmental conditions (light, airborne dust, smoke, water dripping, etc), in in some particularly difficult situations the system's detection range can be reduced, affecting its ability to prevent potential collisions. In such situations, a safer result could be achieved through integration of a video camera-based system with other anti-collision technologies;

question 6: moisture and dust may form deposits on the surface of the camera lenses or blur the images. Frequent cleaning may then become necessary to preserve system performance, and the overall efficiency of the operation is reduced;

question 7: in addition to the topic covered in question 6, the tunnel's difficult environmental conditions can accelerate the degradation of system components: As discussed in question 9 on RFID, excessive maintenance needs may impair positive feedback on the system.

Recently, the questionnaires were provided to the selected TELT construction sites, where these systems are in use, and made available to the equipment operators.

Questionnaire for driver of vehicle equipped with anticollision system

Please mark your evaluation degree inside tables – thank you for your kind collaboration

1. Anticollision system requires changes in drive manner?

no	❑
yes, but it is easy to learn	❑
yes, some days to adapt	❑

2. How many times system warn the operator during a shift?

never	❑
rarely	❑
too frequent (annoying the operator)	❑

3. The anticollision system gives false alarms?

never	❑
rarely	❑
too frequent (resulting annoyance)	❑

4. From your driver experience, could the system automatically avoid potential collisions?

never	❑
one time	❑
more times	❑

5. The warning signal allows a sufficient range to permit the vehicle braking in good time?

no	❑
yes	❑
yes, but extend the detection range is preferable	❑

6. Can the system detect personnel behind the corners in tunnel intersections?

never	❑
rarely	❑
always	❑

7. Can system simultaneously detect multiple obstacles? (for example, pedestrians at the sides, in front of or behind machine)

no, just one an obstacle at a time	❑
rare times	❑
always	❑

8. Can the system provide information on position and distance of detected obstacle?

no	❑
only with regard position	❑
only with regard distance	❑
yes, for both position and distance	❑

9. How maintenance of anticollision system devices is frequent?

low	❑
medium	❑
high	❑

Figure 5: questionnaire for driver of vehicle equipped with radio frequency identification system

Survey for driver of vehicle equipped with video-cameras

Please mark your evaluation degree inside tables – thank you for your kind collaboration

1. Does system with cameras requires a change in drive mode?

no	❑
yes, but it is easy to learn	❑
yes, some days	❑

2. Is the obligation to observe camera for control blind spots of vehicle annoying?

no	❑
yes, depending of screen position	❑
an acoustic signal would be necessary	❑

3. According to your drive experience, had the system avoided possible collisions?

never	❑
one time	❑
more times	❑

4. Does the camera system offer a good distance to avoid collisions?

not sufficient	❑
yes, but depend on environmental conditions (dust, light, etc…)	❑
yes, always	❑

5. Is the cameras system enough to avoid collisions?

no	❑
yes, but is preferable combine it with other systems	❑
yes, it is a good system	❑

6. Given the environmental condition of the yard, is often necessary to clean cameras?

no, one time for shift is enough	❑
quite	❑
more time for shift	❑

7. Over the need of cleaning, how much maintenance the anticollision system with cameras require?

low	❑
medium	❑
high	❑

Figure 6: questionnaire for drivers of vehicles equipped with video-cameras

At the TELT construction site of Saint Martin La Porte access tunnel (Fig.4), a forklift is equipped with an RFID system a (Fig. 7), and laser and infrared systems on bimodal wheeled trucks for prefabricated segment transport during the tunnel construction phase (Fig. 8) have been used. Moreover, the same systems now are present on the rescue vehicles. In the case of RFID, each worker on the site - equipment operators included - wears a tag/badge; an audible/light alarm signal is placed in the driver's cab to signal the presence of pedestrians in the vicinity of the equipment (within an approx. 3 m). The cab audible alarm also performs the vehicle movement clearance verification function and must be deactivated by the operator before starting any operation.

Figure 7: Application of RFID, with details of cab alarm (top right) and the tag/badge wearable by workers (bottom right).

Figure 8: wheeled trucks for prefabricated segments transport, equipped with infrared sensor system.

At the TELT site of Villarodin-Bourget/Modane access tunnel (Fig.4), wheeled mobile cranes are equipped with Blaxtair [24] video-cameras (Fig. 9, 10) and the new rescue and search vehicles are fitted with a double system (infrared and laser combined).

The video camera system detects pedestrians through 3D-cameras in a range up to 7 m: information is passed to the system's onboard image processing unit, such that if pedestrians are present, the unit directly triggers an alarm, and the equipment operator is warned and can react in time to prevent an accident.

These systems were introduced –in addition to some organisational measures and safety procedures- after an accident occurred in 2017, during the construction of the access tunnel, which involved a pedestrian, crushed by a mobile equipment, with heavy but non-fatal consequences. The result was an improvement in underground safety, and no more accidents were recorded.

Figure 9: video-camera system installed on wheeled mobile crane.

Figure 10: details of the screen in the equipment cab.

Currently, the gathering of data through the questionnaires illustrated is ongoing at the above-mentioned access tunnels, in order to evaluate the effectiveness of the anti-collision systems, in combination with TELT in-field experience.

3. CONCLUSION

Even though anti-collision systems remain limited in application in tunnelling operations, they can significantly contribute to interference management. Literature [e.g., 3, 16] and direct experience of a number of leading contractors –among them TELT- confirm the possibility of extended use and effectiveness of these systems to improve both worker safety and the overall operation return also at tunnelling and underground construction sites.

A strengthening of the research work, focused on extensive in-site tests on an increasingly large number of different heavy equipment and anti-collision systems, can contribute to a better definition of the benefits and limitations of the various technologies used in these systems, even in the difficult tunnelling environment. The first-hand suggestions of the operators can substantially contribute to the selection and future improvement of the systems.

Together with a growing safety level of workers at the worksites, two basic topics need further investigation. These are the reduction of false alarms, and the search for improvements in system availability, even in cases of heavy duty use, within acceptable costs.

Technical standards and laws covering the use of machinery for underground works (e.g., EN 12111:2014, EN 16228-2:2014, ISO EN 14120:2015, ISO 12100 [25, 26, 27, 28]), consider the possibility of collision with other equipment, pedestrian or structural components, but at present still do not introduce mandatory endowment of these machines with anti-collision systems.

Some guidelines by authoritative institutions can be of reference in the adoption of anti-collision system in underground work environments (e.g., [29]), and in future, the topic should be considered for updates of the CEN Type C standards, including the anti-collision systems in the list of safety components of machines.

In any case, it is encouraging that all the new equipment introduced by TELT in their underground yards are nowadays fitted with at least one anti-collision system.

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