RELIABLE VEHICLE-AUTARKIC COLLISION DETECTION FOR RAIL-BOUND TRANSPORTATION

Andreas Lehner*, Fabian de Ponte Müller, Thomas Strang, Cristina Rico García
German Aerospace Center (DLR), Münchnerstrasse 20, D-82234 Wessling, Germany
*phone: +49-8153-28-2804, email: andreas.lehner@dlr.de

ABSTRACT: In this paper we present the concept for reliable vehicle-autarkic collision detection developed for a Rail Collision Avoidance System (RCAS) that is based on direct train-to-train communication. Similar to existing systems in air and maritime transport, the RCAS approach allows vehicle-autarkic detection of imminent collisions. Designed as a safety overlay system, it shall warn and advise train drivers in such situations. Broadcasted messages shall allow each railway vehicle to assess the traffic situation in its vicinity under all operational conditions. Apart from an onboard localization unit, which relies on satellite navigation signals, the system architecture does not require any other infrastructure.

Keywords: Railway transport, autarkic, collision detection, train control, RCAS

1. INTRODUCTION

Actual statistics of the International Union of Railways (UIC) show that there are three significant train accidents in Europe every day [1], despite of millions of Euros which have been invested in trackside and in-train safety equipment.

Most of the catastrophes in railroad transport are caused by collisions [2]. Today, only the operation center has an overall overview of the traffic situation, and a train driver has to be informed of a hypothetical collision by the operation center staff. Even with Automatic Train Control (ATC) systems like the future European Train Control System (ETCS) a significant amount of collisions cannot be prevented, because they occur between trains and other kinds of obstacles like construction vehicles, construction workers or pedestrians and vehicles on level crossings.

While maritime, air, and road transport have a vehicle integrated collision avoidance system available or in the development phase [3], there is no satisfying solution of this type of technology in railway transportation. Usually such systems rely on position determination and direct communication among vehicles.

2. TRAIN-AUTARKIC COLLISION AVOIDANCE

Alike we propose a Rail Collision Avoidance System (RCAS), that operates autonomous. For this purpose each railroad vehicle shall be equipped with onboard sensors that provide updated Position, Velocity and Time (PVT) information. PVT and additional data is then regularly broadcasted to all other RCAS equipped units in the surrounding. By analyzing the received messages from other units the complete traffic situation can be assessed, thereby allowing the warning and advising of a train driver in case of a collision threat, long before the danger is visible and early enough to completely avoid it.

While the principle of infrastructure-less vehicle autonomous collision avoidance is well established in aeronautics, as well as it is the case in maritime transport with the AIS

(Automatic Identification System), none of the existing systems is applicable to railway transport, because of its very specific boundary conditions:

1. Movement patterns are highly deterministic because of the guidance by the rails. In conflict situations a train driver can only break or accelerate. The switches are controlled by the railway control centre only.
2. Movement vectors which are in line can also occur in nominal conditions e.g. when trains are coupled or when one train overtakes another one on a double track line. Moreover, the tracks are very close, which requires highly accurate position determination.
3. Punctually there are very high user densities in a railway network like e.g. at large shunting yards. Because the available frequency band is limited, in such areas the resulting high data rate must not degrade the reliability of message transmission.
4. Lines are sometimes under ground (tunnels), under roofs in train stations or they pass through dense forests and hilly areas. Such topological scenarios are challenging with respect to the required range of the direct train-to-train communication as well as for GNSS satellite signal reception.

3. DETECTION OF RAILROAD TRAFFIC CONFLICTS

In railroad transport well-defined collision scenarios can be distinguished in different modes of operation. In **Figure 1** the situation is illustrated for a head-on, a rear-end and a flank collision scenario. In terms of requirements on the range of the train-to-train communications link, the first one is the most demanding, since the remaining braking distances decrease for both trains according to their momentary speed.

Figure 1: Head-on, rear-end and flank collision scenarios in railroad transportation.

In a first analysis published in [4] we investigated different topological scenarios, that describe the different parts of the whole railway network, and identified regional lines, train stations and shunting yards as those scenarios which are relevant for the RCAS system design. Main lines with high speed services are not considered, because there the safety level is already very high due to extensive technical equipment and train control mechanisms.
For the listed scenarios the maximum speed is 160 km/h. In case of emergency braking the maximum braking distances are in the order of 1 km. Depending on the weather and rail conditions this can increase due to reduced fraction. Moreover, to allow for a secure (non passenger imperilling) braking of fast passenger trains, up to 2 km are necessary with the corresponding brake configuration. For the head-on collision scenario this means we need to guarantee a communication range of at least 5 km and need to have a high message repetition rate [5] to loose a minimum of braking distance when the two trains approach the communication range.

3.1. RCAS System architecture

On board of each rail vehicle an intelligent RCAS unit is foreseen, comprising a transceiver and a processor unit as illustrated in **Figure 2**. For accurate track resolving localization, a combination of GNSS receiver, odometer and eddy current sensor can be used [6]. The last one not only improves the accuracy along the track by detecting rail clamps, but also allows identification of switches and the switch stand by unique signatures. Aided by an electronic map this guarantees precise PVT information even in tunnels, under roofs of train stations and in shunting yards.

In order to avoid collisions by overlapping cargo, to survey the catenary and the track, or to monitor the end of the train, a camera can be installed and connected to provide additional safety relevant information. Furthermore, an interface to an electronic schedule like the German EBuLa can give information on the planned route and speed of the train. In the future ETCS will even support online updates on this data.

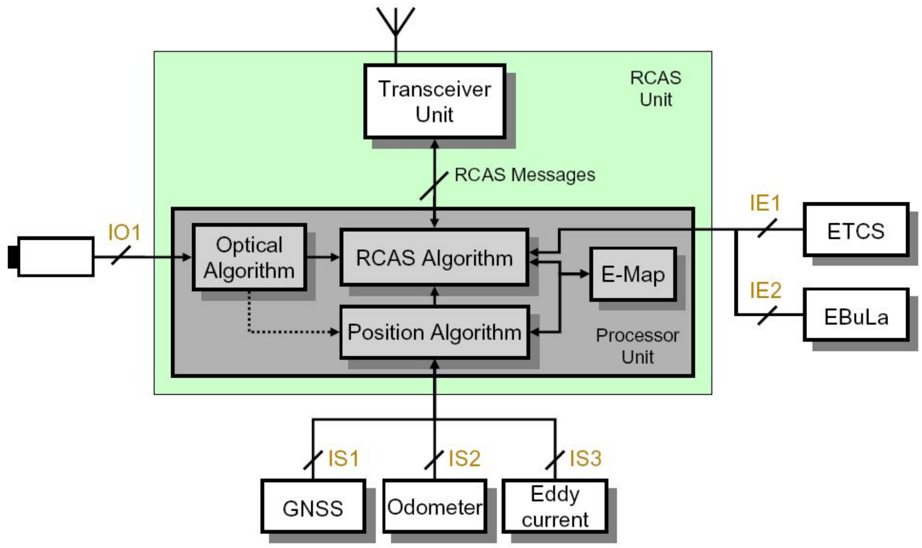

Figure 2: RCAS system unit architecture.

The core of the system is an algorithm analyzing the received information from other trains together with the PVT and train data of its own carrier. Thus it allows to advise the train driver against a potential collision, or even to initiate braking to avoid it.

3.2. Vehicle-autarkic collision detection

Each RCAS unit produces messages with a fixed length. These messages are transmitted with a variable rate in a broadcast mode depending on the own speed and the traffic situation in the vicinity. The net size is of the RCAS messages is 150 bits. For the proposed format we refer to [5]. First of all the message type indicates the format of the Position and Route Information (PRI) block. If there is a track selective position information present, the track ID, the distance from the tracks starting node, the movement direction and, if available, the information on the planned route are transmitted. Alternatively latitude, longitude and heading are broadcasted. The train ID includes information about its operator, the type of train or vehicle and its danger status. The type of train information enables prioritization of e.g. a passenger train that passes a shunting area. The danger status can be used to notify others of an extended loading gauge or if dangerous goods are carried. The current speed, an estimate

of the braking distance, and the forward and backward length of the train with respect to the localization unit are included in the message to allow other trains to identify potential collision points and to determine where and when warnings and braking advisories must be initiated.
The most important property of a collision avoidance system is its reliability in detecting collisions in time. Moreover we must guarantee that regular operation conditions do not lead to warnings, because this would slow down train runs. Moreover, regular false alarms would

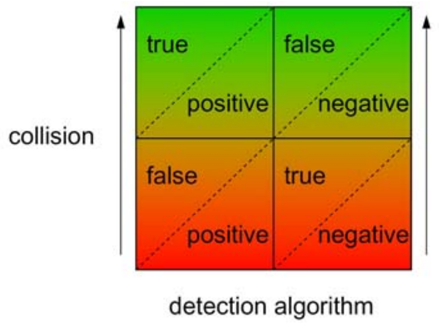

Figure 3: Contingency table for a collision detection algorithm.

cause train drivers' to mistrust the system and eventually to ignore it. That means we have to minimize missed alarms (false positive) and minimize false alarms (true negative) as illustrated in the contingency table in **Figure 3**. This goal is particularly difficult to achieve in railway transportation. Imagine a single track line with a passing point at a small station, where two railcars are approaching, or one has already stopped in the station.
In order to distinguish collision scenarios from regular operation, it is very helpful to look at the estimated braking distances. In regular operation there is always enough margin to allow for a dosed braking. Thus, if the distance to another train on the same route approaches the sum of the braking capability limits of both trains, the RCAS system shall act.

Alert and advisory (command) concept:
Because of the relatively high speeds of trains and the long braking distances, an alert and advisory (or command) concept, similar to the aeronautical TCAS, promises a major safety gain. In the first step a Traffic Alert (TA) signal shall warn the train driver in case of a detected close approach to another RCAS unit on a collision course. TA will be activated with a fixed time t_{Alert} prior to the time when the train has to start braking, given that it proceeds with the momentary speed. Thus, the train driver is prepared to receive a Braking Command (BC) in a second step, which is signaled after t_{Alert} seconds in order to avoid the collision.
As an example **Figure 4** illustrates this concept for the front collision scenario. The distance between TA and BC is given by $D_{Alert}(v) = v \cdot t_{Alert}$. To allow for a safe braking, a guard distance $D_{Guard}(v)$ is added to the braking distance $D_{Brake}(v)$ to assure that the trains come to a full stop under all environmental conditions.

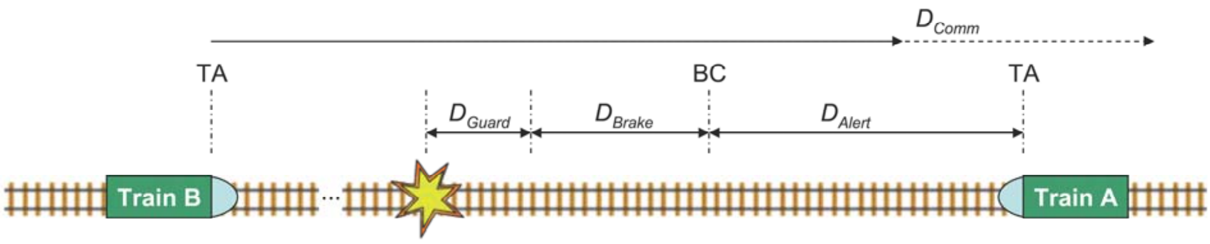

Figure 4: Illustration of Traffic Alert (TA) and Braking Command (BC) concept.

Braking distance estimation:
The braking distance of each train mainly depends on the following parameters: Speed, slope of the track, brake type, brake configuration, number of axels, and ratio braking weight to train weight. While the track slope is provided by the electronic map, all other parameters are train or vehicle specific parameters which are either pre-assigned or they can be determined by sensors.
An estimate of the braking distance s_B can be calculated with e.g. the Mindener equation [7]

$$s_B = \frac{3,85 v_0^{\ 2}}{6,1\psi(1+c_1\lambda/10)+c_2 i_m}, \tag{1}$$

where v_0 is the speed at the start of braking, ψ, c_1 and c_2 are higher order function of v_0 which depend on the brake type, brake configuration and number of axels, i_m is the mean slope of the track, and λ is the percentage of brake power (ratio braking weight to train weight). Equation (1) is valid for passenger trains only. For a modified version of (1) addressing freight trains and for more details on the parameters we refer to [7]. To calculate the total braking distance D_{Brake} we need to add the distance depending on the reaction time t_{React} of the train driver: $D_{Brake} = v \cdot t_{React} + s_B$.
Although such calculations can provide good estimates and one can even think of expanding the model to take e.g. aging of brakes into account, the real braking distance might vary due to the fact that adhesion and friction between wheels and rails are changing depending on the environmental conditions, which are difficult to be quantified. In order to minimize false alarms in regular operation conditions and to efficiently use the track infrastructure, the braking distance shall not be overestimated. On the other hand, an underestimation of the braking distance would cause collisions at low speed. Therefore we propose to add a guard distance D_{Guard} as depicted in **Figure 4**.
Under the assumption, that all involved vehicles are aware of the critical situation, that means we can guarantee that the communication range D_{Comm} is larger than the sum of the total braking distances (see **Figure 4**), we can further assume, that all train drivers will follow a BC. That means each involved vehicle is able to determine a common point on the track (crash symbol in **Figure 4**), where it must come to a full stop. This finally leads to the absolute points on the track for TA and BC signaling.

The main drawback of the Mindener equation is that it is not suited to perform detailed position, speed and acceleration over time analysis. In order to precisely determine evolution of position, speed and acceleration a new approach based on a three stage braking process

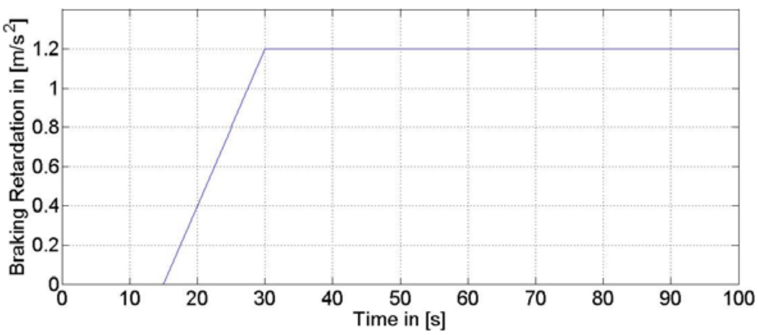

Figure 5: Three stage process modeling the brake behavior of trains, e.g. for $b_{\max} = 1.2$ m/s^2.

shown in **Figure 5** is developed. Brakes do not apply immediately but have a certain response time. After this response time the air leaves the brake pipe gradually and the brakes start applying. This is the development stage which is given by the Development Time and after that full braking pressure is applied on the wheels and the train decelerates with braking retardation $b_{\max}$. We chose standard values of 10 seconds for the response time and 15 seconds for the developing time for the following analysis.
As next step we performed a simulation comparing the three stage braking model and the Mindener equation, seeking the best relation between the percentage of brake power λ and the maximum braking retardation $b_{\max}$. By adjusting the maximum braking retardation $b_{\max}$ we calculated the braking distance over speed that approximates the Mindener equation from an MSE point of view, shown in **Figure 6**.

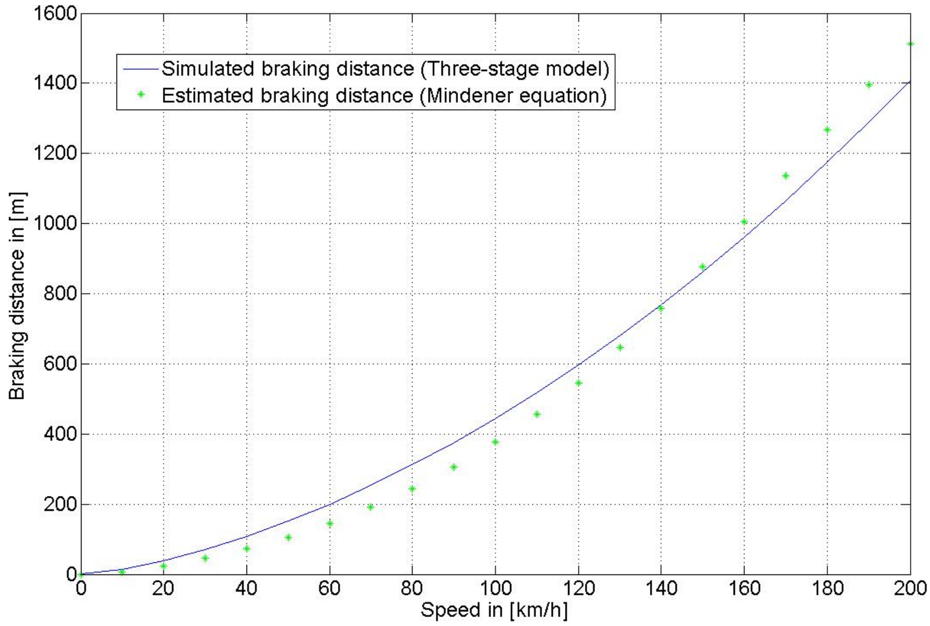

Figure 6: Comparison of braking distance over initial speed between simulated three-stage braking and the Mindener equation estimate for λ =170 (brake config. ‘P’, 90 axels, i_m = 0).

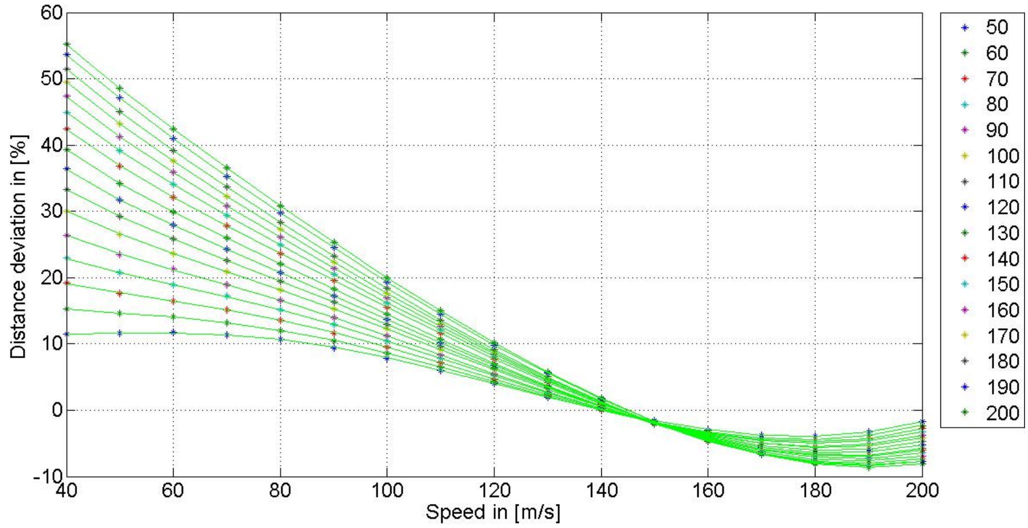

Figure 7: Distance deviation of the fitted three-stage braking model from the Mindener equation estimate for different values of the percentage of brake power λ.

Repeating this process for different λ and approximating with a second order polynomial, yields to $b_{max} = f(\lambda) = 2.326 \cdot 10^{-5} \lambda^2 + 4.434 \cdot 10^{-3} \lambda + 0.109$. Nevertheless, a remaining error exists between both curves. This speed dependent deviation is shown in **Figure 7** for different values of the percentage of brake power. In a final step this deviation can be additionally considered in the guard distance, to correct for it.

Analysis of the dynamic behavior:

An analysis of the dynamic behaviour for two trains driving on a head-on collision course was performed, using this three-stage braking model on each train. Simulations revealed a great improvement in the accuracy of the computation of the estimated collision point (ECP) when the past dynamic behaviour of a train is taken into account. **Figure 8** shows the space-time curves of two trains separated 3000 meters from each other. The black curves represent the assumption that each train is going to continue moving with the current speed. The intersection of these lines represents the estimated collision point in that case. Furthermore we can account for the extreme cases where the train starts accelerating with full power around

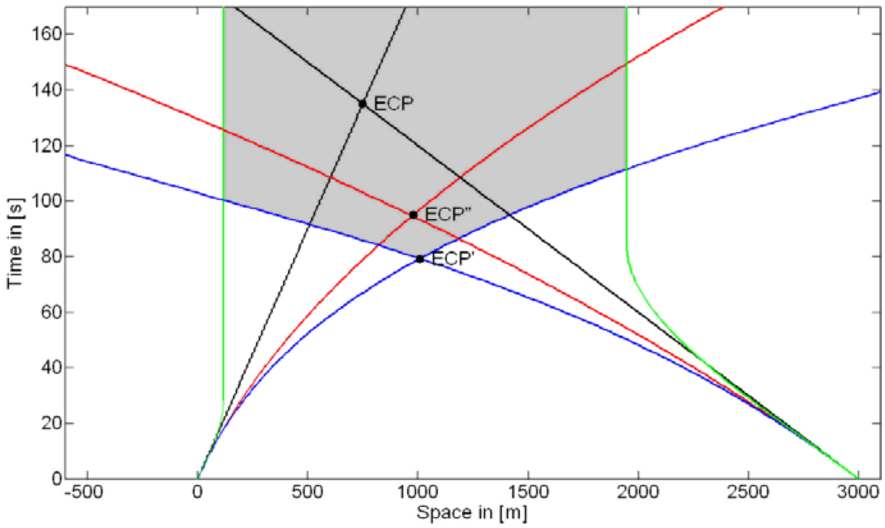

Figure 8: Space-time diagram of two trains in a head-on collision scenario with both trains initially accelerating.

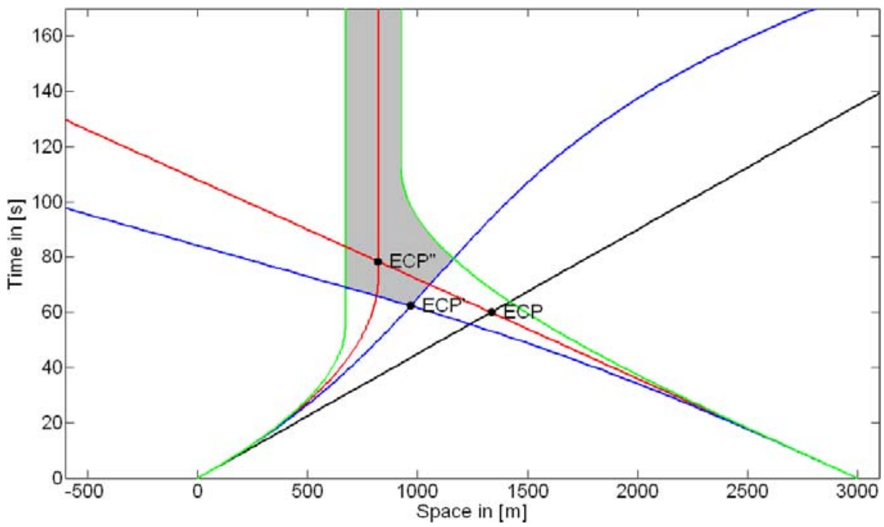

Figure 9: Space-time diagram of two trains in a head-on collision scenario with one train initially decelerating.

0.5 m/s^2 (blue curves), which would be a worst case assumption, or if it would brake with full braking retardation around 0.6 m/s^2, giving the grey area in **Figure 8** with all possible ECP's. When the train is already immersed in a braking process, like it is the case in the example in **Figure 9**, the ECP computed with a constant velocity assumption can lie outside the grey area. To overcome this problem the assumption that the trains keep their acceleration/deceleration in the future was followed and showed best results in simulations (red lines in **Figure 8** and **Figure 9**). This assumption rests on the fact that trains are usually not changing their accelerating/brake profile abruptly. Especially in regular operational scenarios where rear-end and flank collisions are threatening, the reliability in detecting collision and at the same time the prevention of false alarms can be drastically improved taking a three-stage braking model and the actual acceleration/deceleration status into account.
Since information about the switch stands on the track ahead are in general not available/reliable, the here presented approach is applied to assess the conflict potential of all trains that have a common track ahead within the RCAS communication range.

SUMMARY AND OUTLOOK

In this paper we presented a novel concept for reliable conflict detection in rail-bound transportation based on a train control overlay system exploiting direct train-to-train communications. The content of the broadcasted messages allows each railway vehicle to assess the traffic situation in its vicinity. The presented conflict detection concept provides instant information to train engine drivers in case of imminent collisions and many other threats on railroads that cause most of the accidents today. At the same time it allows for a more efficient use of rail infrastructure in the future.
In the future we plan to further improve the performance of the RCAS collision detection algorithm by taking additional information from the track map, e.g. changing slops or physical speed limits in ahead lying track sections, into account.

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