19th ITS World Congress
Vienna, Austria
22 to 26 October 2012
smarter on the way

Towards Autonomously Driving Trains on Tracks With Open Access

Oliver Gebauer*, Wolfgang Pree
Software & Systems Research Center
Univ. Salzburg, Austria
firstname.lastname@cs.uni-salzburg.at
Gerhard Hanis, Burkhard Stadlmann
School of Engineering and Environmental Sciences
University of Applied Sciences Upper Austria, Wels
firstname.lastname@fh-wels.at

Abstract

Compared to automobiles on roads, trains have less degrees of freedom as they are bound to railroads. Thus, it should be more straight-forward to let them drive autonomously compared to automobiles. Several autonomous trains and subways already exist; however they operate on closed tracks. Typical examples are airport trains, also known as people movers. This paper sketches the conceptual, technical and legal challenges towards autonomously driving trains on existing railroads that are freely accessible and thus require reliable obstacle recognition. We try to generalize the experiences made so far in several large-scale research projects that aim at automating small, secondary railways. We summarize the results of a prototypical autonomous train system that we called auto*BAHN*.

KEYWORDS:
autonomously driving trains, obstacle recognition, simulation of railroad traffic, train control system, secondary lines, cyber-physical systems.

1. Motivation

A significant reason for travelers to choose automobiles instead of trains is the hassle with train schedules and the low availability of trains, especially on secondary lines. These lines are often sparsely occupied and the time between trains can take up to two hours, but through their dense rail network (see Figure 1) they transport a significant amount of passengers to main lines. Raising the attractiveness of secondary lines is therefore a key to higher profitability on main lines. However, increasing the frequency of trains is expensive and often not feasible, as long as the running costs cannot be covered.

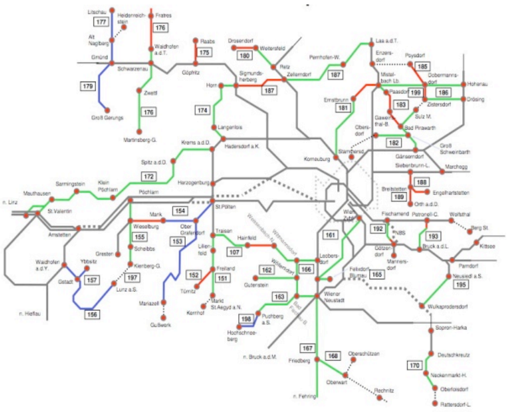

Figure 1 Secondary lines in Lower Austria (courtesy oebb.at).

The traditional concept of trains being composed of an engine and a number of cars bears a natural limitation of attractiveness for passengers. The more passengers they serve, the more stops have to be made, which increases the total travelling time and therefore reduces attractiveness (and vice versa).

One solution to this dilemma would be the reduction of the size of trains and at the same time an increase in their frequency to an extent, which would render schedules obsolete for passengers, if not for the enormous costs of the additional drivers that this would require. Small, powered and autonomously driving cars could solve this problem.

The goal of developing an autonomous train system based on obstacle recognition is to raise the attractiveness of trains without the extra costs for drivers. Our calculations predict the doubling of passenger frequency while cost recovery is raised from an average of 30% up to 60% on existing secondary lines.

Chapters 2 and 3 of this paper provide a more detailed introduction to the system. Chapter 4 presents the simulation results and chapter 5 the main results of the obstacle detection system. The autonomously driven cars are operated within a special train control system which is described in chapter 6. Figure 2 gives an overview of the main system components. The obstacle recognition uses multiple different sensor technologies as well for redundancy reasons several sensors of the same type. Based on the used sensors the data fusion module determines the nearest obstacle in front of the train and monitors the sensors' activity. A Train Control

System (TCS) provides the base framework of the current auto*BAHN* system. It consists of a central station, a digital data radio system and an on-board computer which supervises the train. The TCS is extended by a speed supervision and control module. The individual systems are connected to the communication layer which enables the nodes to exchange data between them. The Brake & Engine Control (BEC) receives from the TCS commands indicating at which speed the train shall drive. In consequence the BEC shall control the trains' actual speed by autonomous actuation of the engine / breaks.

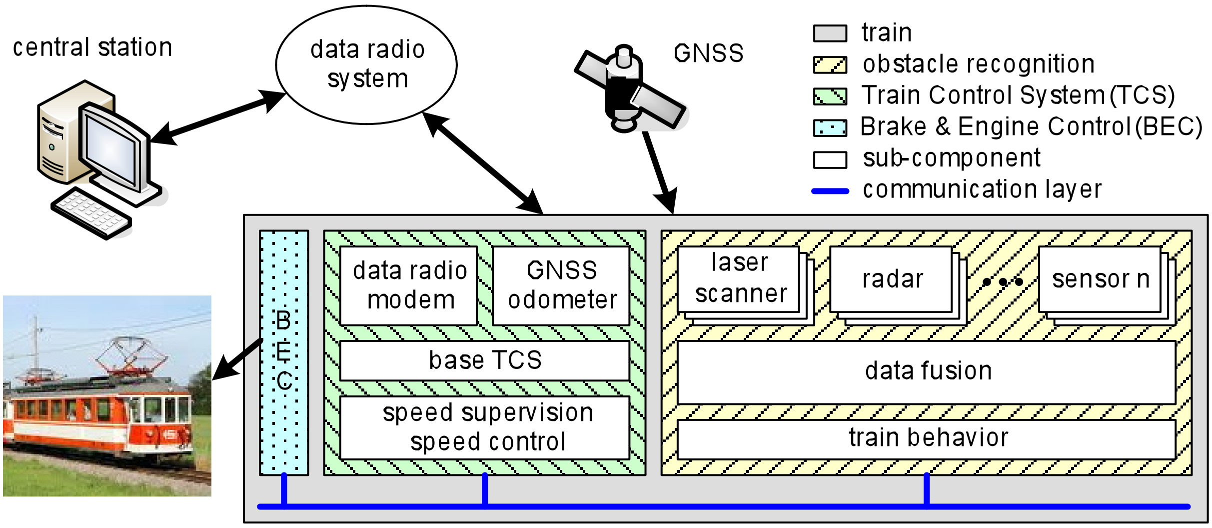

Figure 2 Schematic overview of the auto*BAHN* system.

2. Feasibility of autonomous trains

Compared to roads rail traffic offers attractive advantages for automation. The unsolved legal problem in assistance systems of road cars "Who is responsible in case of accidents?" is sharply reduced as access to rails is restricted by law and traffic is controlled by train control systems. On secondary lines, train speeds are below 100 km/h, which reduces the required visual range compared to main line trains.

To be economically viable, we consider it important to develop an automation concept which allows the use of existing railroad infrastructure with a minimum of required changes. This includes the challenge of driving on open, freely accessible tracks, opposite to already existing fully enclosed driverless subway systems or people movers at airports, etc.

Europe has numerous secondary lines, which have only local traffic and are connected to a main line at one end. So, there is no need to mix human-driven with autonomously driven trains in one system. Thus, switching to autonomous trains can be accomplished independently, step by step.

An important role for the regulatory certification of new railway systems requires “globally at least as good” safety compared to existing procedures and systems. We see realistic chances to even improve the safety of train traffic with autonomous trains, by improving technical visibility during bad weather conditions and significantly reducing the total weight of the cars.

3. The autoBAHN concept

Supported by the Austrian Climate and Energy Fund [8] and the Austrian Research Fund [9] the auto*BAHN*[1] project was started in 2008 to demonstrate the feasibility of autonomously driving trains [11]. By the end of 2011 the prototype described herein has been able to drive autonomously on an existing and unmodified railroad by use of an obstacle recognition system, utilizing a GPS-based train control system.

The auto*BAHN* concept can be summarized as follows:

1. Replace the driver's function with a purely car based obstacle recognition system with a range of 100 meters for typical train speeds on secondary lines up to 80 km/h for obstacle sizes larger than 20 x 20 cm.
2. Place autonomous load balancing and a purely radio-based automatic train control system on a secondary line with a minimum amount of turnouts.
3. The train navigates with a continuous positioning precision better than 1 m.
4. The headway of trains is reduced to between 6 and 15 min.
5. The cars’ capacity is 20-30 passengers, its’ length 11 meters with an estimated weight below 20 to.
6. Audio and video communication facilities between all cars and central control unit for passenger security.
7. Constructional changes of rail track infrastructure are limited to few additional turnouts and simple barriers at stations for improved passenger safety.

To set up our prototype we were able to use and adapt an existing car from the Austrian railway company Stern & Hafferl on its line between Gmunden and Vorchdorf. For the

---

[1] *Bahn* is a generic German term; it can be used for both roads and railroads, though it is more associated with trains, such as in Deutsche Bahn, the company that runs trains in Germany. The German Autobahn was the predecessor of the American freeway. In our context an auto*BAHN* is an autonomous Bahn.

important task of surveying and mapping the track, masts, poles, signs, stations, buildings and vegetation to a precision of 2 cm were registered and stored in an appropriate database. For this task the cutting-edge 3D-laser VZ-400 from the company Riegl [5] was used.

4. Simulation to determine logistical key factors

For economic reasons small secondary lines usually utilize single instead of double tracks. A single line is sufficient as long as the frequency of trains is low. With the auto*BAHN* concept, the number of cars on the track increases by an average factor of 3. Therefore it was necessary to determine the key variables which influence the performance of the system. We developed a discrete event simulation to validate and fine-tune our concept. In particular, the following points should be addressed:

- the number of cars required to assure the intended headway time
- the amount of time that has to be spent for waiting in diverging sections for oncoming traffic, depending on car frequency, number and position of diverging sections
- the total mileage of cars
- the number and optimal position of additionally required side tracks
- the average and worst case waiting and travelling times for passengers

We simulated the auto*BAHN* concept for a local secondary line with a length of 14 km, an average of 400,000 passengers per year, 13 stops and 2 existing side tracks on the line. With the traditional schedule a passenger has a travel time of 25 minutes. 14 rides are scheduled per day in each direction, using 2 trains.

After optimizing the position of the diverging sections we found an optimum configuration for the auto*BAHN* with 3 additional side tracks, 6 cars and 9 min headway, resulting in 5:02 minutes average and 14:19 minutes maximum passenger waiting time. The waiting time of cars for oncoming traffic in diverging sections increased the travelling time by ca. 30%. These numbers are even more promising as we used the worst-case scenario of passenger frequency measuring, including a short period when 60 passengers arrived simultaneously at a station.

5. Obstacle recognition

Solving the most challenging problem of the auto*BAHN* concept, the replacement of the driver, differs from similar problems in road cars, as they are currently under development at Google [10] and certain car manufacturers for their popular driver assistance systems.

The following issues have to be addressed:

(1) Rail traffic has a precise definition of the term structure gauge. Both the horizontal and vertical extension of the car have to be respected within very small margins, especially in curves, where overhanging vehicle parts must be considered.

Figure 3 Is the person in or outside the structure gauge?

(2) The braking distance is significantly longer than in road traffic, typically by a factor of more than 5.

(3) Intentional dangerous actions like suicides or careless automobile drivers at railway crossings play a major role in rail traffic.

(4) Though the course of the track is well-defined and the danger of unexpected damages on the driveway is reduced compared to roads, significant confusion can be caused by vegetation, snow, mudflows, avalanches, broken down tree branches or criminal assaults.

Figure 4 Flying plastic ribbon as fake obstacle example.

Together with the Austrian Institute of Technology [12] we experimented with several different sensor types, in particular laser scanners, optical and infrared mono and stereo cameras, radar and ultrasonic systems. Image recognition has so far only been applied for the identification of rails.

Our conclusions can be summed up as follows:

- Technical characteristics of sensors like pixel- or angular resolution, range, color depth, focal length, data bandwidth, accuracy, wavelengths and others are playing a major role in evaluating and identifying the right setup and obtaining useful results.
- Mounting positions of sensors on the car and the avoidance of vibrations significantly influence the quality and reliability of results.
- Stereo cameras and laser scanners require maximum available computer performance and data throughput. The rate of (stereo) frames per second must exceed 3 to assure continuous and safe obstacle detection (see figure 5).
- Navigational precision can severely influence the rate of false positives before and in curves (see Figure 3 as an example).
- An adequate data fusion algorithm is based on the individual characteristics of sensors and should include heuristics for certain situations like railway crossings, train speed, visibility, precipitation or snow on the rail track (see Figure 4 as an example)..
- Special care must be taken for the timing behavior of different sensors.

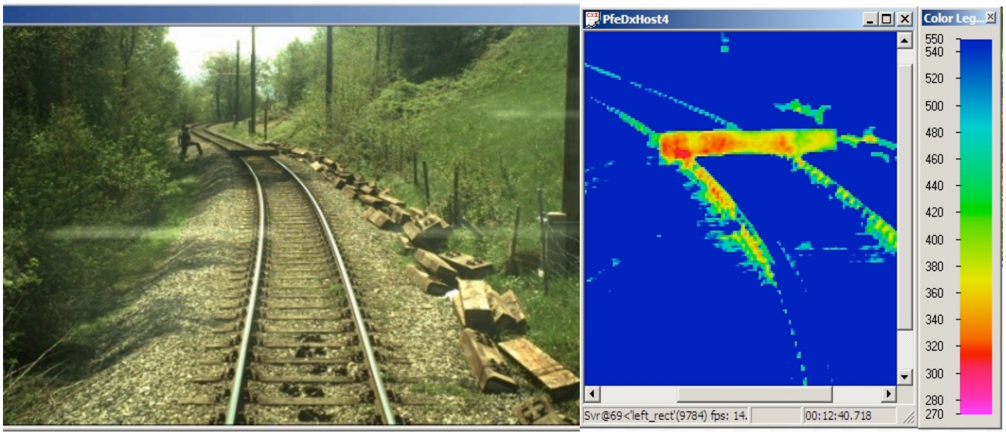

Figure 5 Stereo camera detection of obstacles (courtesy AIT [12])

6. Train Control System based on Global Navigation Satellite System

For the development of autonomous train systems an infrastructure with on-board computers on every train for continuous determination of train location, movement monitoring and communication with a central station is required. To demonstrate the feasibility of autonomously driving trains on secondary lines the Train Control System (TCS) already deployed at Stern & Hafferl's lines is being used as the base infrastructure. The key features of this TCS are: a central station for dispatching, trains with on-board computers, data radio communication between trains and the central station, autonomous train location, cab-signaling, supervision of the Movement Authorities (MA) of the train. The implemented

TCS delivers these features at low deployment and operation costs. A trial performed under human supervision based on this system was successfully completed during the regular operation on the secondary line.

TCS architecture

The TCS [7] is a distributed real-time system with a proprietary data-radio system as the shared network layer and centralized control for dispatching. The central station is responsible for the conflict-free generation of MAs, maintaining the communication to the trains via the data radio system and the transmission of the locally generated RTCM correction data to the trains. It also provides an interface to the dispatcher which shows a complete real-time view of the line. The schematic view shows the line on one hand and a scaled electronic time table including both the planned and actual train movements on the other hand.

The communication between the central device and the trains relies on a line-specific data radio system, thus no expensive further line-side equipment is required. The on-board computer is responsible for determining the trains' location on the line based on Global Navigation Satellite System (GNSS) position data and an odometer. The result of the sensor fusion is matched against a digital line atlas to retrieve a position using line-based coordinates. The digital line atlas contains specific geographic, topological and logical information about the track and is stored on each on-board computer and at the central station. Due to omitted track side signals, the train driver is informed via displays (cab-signaling) of the most important information, like current location, system state and received MA. Consequently, the computer supervises the correct execution of the MA by the train driver. Moreover, it also monitors the movement of the train and will automatically activate the emergency brake if the driver tries to pass beyond the limitations of the given movement authority.

This TCS already features similarities to the European Train Control System (ETCS) level 2 like cab-signaling and data radio communication though it is developed for secondary lines. Furthermore, the feasibility of this system has been proven by successful roll-outs on three Stern & Hafferl's secondary lines in Austria and a current roll-out on another one. The combined track length that is covered with this kind of TCS is more than 140km.

Extensions to the base TCS

On the selected secondary line one train has been modified to allow autonomous driving while it is under constant supervision by a train driver. Regular passenger transportation with a human driver is still possible, as all modifications have to be fully revertible. To be in line with this constraint, a solution containing several hardware modules and software extensions to the base TCS were developed. Figure 2 illustrates the main components of the train equipment for autonomous driving. At the current stage more advanced systems for autonomous vehicles, such as door control, and smoke and fire detectors, are not integrated, since the goal was to demonstrate the feasibility of autonomous rail travel. Additional modules can be added in a straight-forward manner due to the flexible communication layer.

Since all necessary information concerning automatic train movement is exchanged within the base TCS between the train and the central station, the required software modifications have to be accomplished on the train side. As a result the experimental modifications will not affect the safety of the base TCS which is deployed on the other trains. This is of vital importance since the test drives take place during regular operating hours of the secondary line.

The communication layer is used for real-time data exchange between the nodes, for example, between obstacle detection and TCS. It is based on an industry proven field bus plus higher level protocols to ensure its reliability.

As described in section 5 the obstacle recognition system constantly searches for potential threats along the trains' path. If one or multiple obstacles are detected, it sends this information plus the detected distance between car and nearest obstacle via the communication layer to the TCS.

The Brake & Engine Control (BEC) developed by Siemens and ELIN EBG Traction receives a reference speed from the TCS which the train maintains. Depending on the current state, velocity, acceleration and the reference speed, the BEC will actuate the gate contactors of the electric drive or the electric and the pneumatic brakes of the train to control its speed.

The extensions to the train side TCS can be briefly listed as: brake curve calculation, continuous speed supervision and control, reaction to reported obstacles, trip planning and selection of brake intervention.

The brake curve calculation is based on a given MA and is performed for the emergency as well as the service brake. It factors in the gradient profile, the trains' length and the static and dynamic speed restrictions along the planned route. The former restriction is included in the digital line atlas, while the latter is received with the MA. Although it was possible to make certain simplifications, like constant brake parameters, the implemented algorithms are to a large extent in line with the proposed brake curve calculation of the ETCS [6].

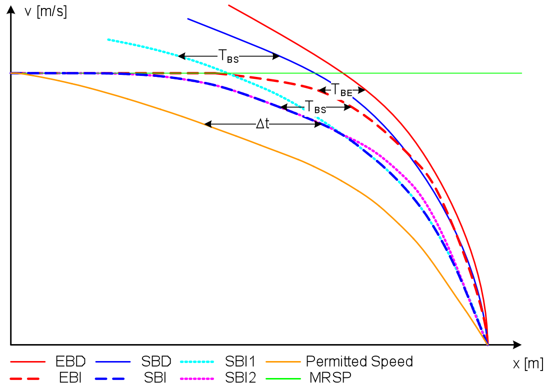

Figure 6 Principle illustration of the brake curves based on ETCS.

The Most Restrictive Speed Profile (MRSP) contains all speed limitations. The emergency and service brake deceleration curves (EBD, SBD) indicate at which point full force of the corresponding brake has to be applied to keep the train within the given speed and position limits. The intervention curves (EBI, SBI) specify when the brakes have to be applied to build up full brake force at EBD and SBD. Therefore they are subsequently derived from EBD and SBD. This step is performed via safety considerations and the related safe brake build up times (T_{BE}, T_{BS}). Given a defined MRSP and a target location figure 6 indicates how the curves shall be calculated to safely stop the train in front of the target.

Consequently these brake curves are used for continuous speed supervision and brake selection. Moreover they also serve as a reference to calculate a Permitted Speed curve a time Δt before SBI. It can be seen as an indication of the maximum allowable speed at which the system is currently permitted to drive. In consequence the speed control add-on of the TCS is based on it. In order to save processor time while the train is driving, parts of the brake curve calculation are performed in advance. When a MA is received, the TCS plans the trip from the current location to the target destination. During normal operation it uses the planned curves to control and drive the train to its planned stop location. If an obstacle is reported to the system while in driving mode, separate brake curves are generated and the mode is switched to “approaching obstacle”. These curves are updated every time the reported distance to the object changes. The goal on the one hand is to retain the planned curves available to the speed control in the event that the obstacle is temporary and therefore save computation time, and on the other hand to react adequately according to the obstacle.

Results

During regular operation of the secondary line several fully autonomously test trials under human supervision were performed. As a consequence all extensions to the base TCS and the communication layer between obstacle recognition, TCS and BEC had to be operational. Hence automatic speed supervision and control, based on brake curves, were successfully tested. We are now able to drive from any starting location on the track to the end of a given MA and stop at all stop stations within it. In addition reported obstacles are processed within the speed control subsystem.

Figure 7 shows a computer controlled trip from one station at position 11524 meters to the next one at 11021 meters. This journey includes 2 MRSP sections; the first one with 40km/h, the second with 20km/h. The reference speed is derived from the calculated permitted speed and therefore it's based on the used brake curve system. As shown a reasonable reference speed has been calculated by the extended TCS and sent via the communication layer to the BEC. Overall the prototypical speed control and supervision system ensured that the trains' speed will be within the boundaries of the MRSP, the given MA and that it stops the train at the planned destination.

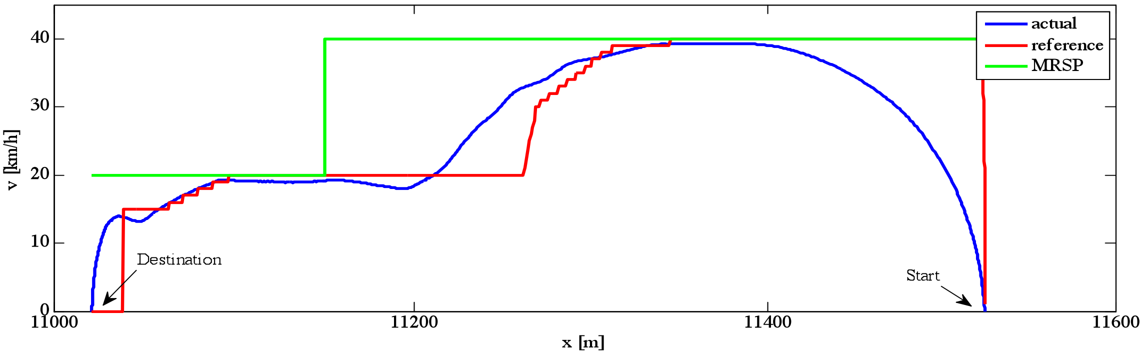

Figure 7 Speed comparison of an autonomous test drive.

7. Summary and implications

We are convinced that the auto*BAHN* concept could significantly improve the attractiveness of passenger trains and lead to a better use of available railroad capacities and strongly improved economics of the rail system on secondary lines. This is especially true for Europe with its dense network of such railroads.

Given the determination of manufacturers and legal authorities, we are sure that within five years, the auto*BAHN* concept as outlined above could be deployed on existing railroads. This is, for example, not expected for fully autonomous driving with automotive vehicles. With the auto*BAHN* prototype system the main technical hurdles to autonomous rail transport offers proof of concept.

References

[1] Rustemeier, Carsten; Nachtigal, Vitalij: RailCab – *A New Modular Rail System*, 4th International Conference Trans-Mech-Art-Chem ; May 11-12, 2006, Moscow, Russia

[2] Sondermann-Wölke, Christoph; Müller, Thomas; Geisler, Jens; Trächtler, Ansgar; Böcking, Joachim: *The Active Guidance Module of a Rail-Bound Vehicle as an Application of Dependability Oriented Design in Self-Optimizing Systems*, Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2008, August 3-6, 2008, Brooklyn, New York, USA

[3] Web reference RailCab: http://www.railcab.de

[4] Web reference CargoCap: http://www.cargocap.com

[5] Web reference: www.riegl.com

[6] ERTMS User Group, *Description of the brake curve calculation*, EEIG 97E881 Version 7A, 25.09.2008

[7] Stadlmann, Burkhard; Mairhofer, Stefan; Hanis, Gerhard: *Field Experience with GPS based Train Control System*, European Navigation Conference on Global Navigation Satellite Systems, 2010, Braunschweig, Germany

[8] Web reference Austrian Climate and Energy Fund: http://www.klimafonds.gv.at/

[9] Web reference Austrian Research Fund: http://www.ffg.at

[10] Web reference Google: http://googleblog.blogspot.com/2010/10/what-were-driving-at.html

[11] Gebauer, Oliver: *Ein Modell für eine autonom fahrende Eisenbahn und seine fallstudienbasierte Evaluierung*, Dissertation in progress (german language), Johannes Kepler Universität Linz, Austria, Institut für Wirtschaftsinformatik/Software Engineering, 2012.

[12] Web reference AIT: http://www.ait.ac.at/departments/safety-security/business-units/safe-and-autonomous-systems