Towards Autonomously Driving Trains

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Compared to cars 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. The paper sketches the conceptual, technical and legal challenges towards autonomously driving trains on existing railroads. We try to generalize the experiences we have made so far in a research project that aims at automating small, local, self-contained railways.

Key words: autonomously driving trains, simulation of railroad traffic, cyber physical rail system

1. Motivation

Trains are a widely unpopular means of mass transportation, compared to road traffic with automobiles. Their major shortcomings are the lack of privacy, its inflexibility due to the requirement of schedules and their slowness, caused by continuous stops for entering and exiting passengers.

On railroads, the concept of trains, being composed of an engine followed by a number of cars, has not been changed since trains were invented centuries ago. This traditional concept reduces the attractiveness for passengers: The more passengers it shall serve, the more stops have to be made to give them access to the train. More stops in turn reduce the average speed of the train.

If we could split a train in many small 'trainlets', each about the size of an automobile, we could overcome this limitation: Passengers sitting in a trainlet have the same destination and travel directly there. As a train driver for each trainlet would not be economically feasible, the trainlets need to drive autonomously.

2. Context and aims of the socalled *Auto-Bahn* project

What would be suitable railroads to start with? We consider it important to use existing railroad infrastructure. Otherwise, the autonomous trainlets could probably never move beyond research prototypes [1, 2, 3, 4]. Besides its main railroads, Europe has numerous local railroads, called *Nebenbahnen* in German. Figure 1 shows on the left a map of the *Nebenbahnen* in Lower Austria, one province of Austria (upper right map). The province of Lower Austria has a size of ca. 20,000 km^2, about one quarter the size of Maine. All colored lines are *Nebenbahnen*. The gray lines are main railroads.

Nebenbahnen are often self-contained, that is, they have only local traffic. So there is no need of mixing human-driven and autonomously driven trains in one system. Thus, a switch to autonomous trainlets can be accomplished independently for each *Nebenbahn*, step by step or in parallel.

We have started the Auto-Bahn[1] project this year. Its aims are to: (1) show that autonomously driving trainlets are technically feasible (2) find economically attractive scenarios (3) demonstrate trainlets for a limited time in an experimental setup on a selected *Nebenbahn* in Austria, and (4) update the legal framework to get the permit for transforming *Nebenbahnen*.

Regarding (1) we are optimistic to overcome the technical hurdles, because the two key problems, navigation and obstacle recognition, have already been solved as the DARPA Grand/Urban Challenges have demonstrated. We focus on experimenting with several sensor types, in particular laser and radar, as well as image recognition. For example, we will harness the cutting-edge 3D-laser VZ-400 from Riegl [5].

[1] *Bahn* is a generic German term; it can be used for both roads and railroads.

Regarding (2) we use discrete event simulation to fine-tune the trainlet concept. The next section presents preliminary results. Probably the most difficult hurdle will be (4), the legal framework for operating autonomously driving trainlets.

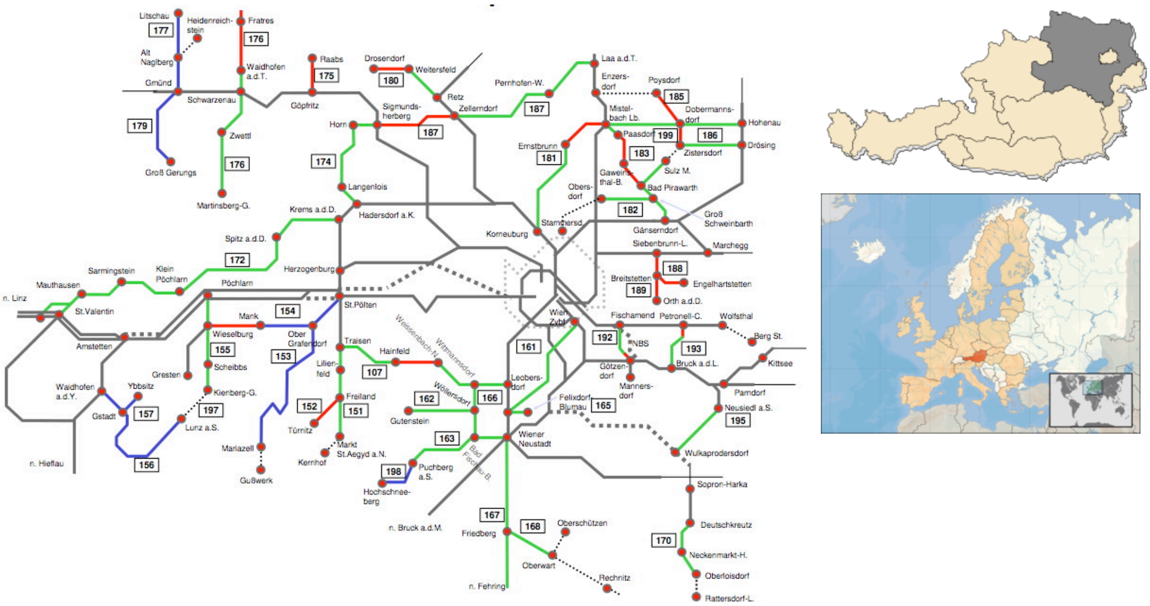

Figure 1. *Nebenbahnen* in Lower Austria (courtesy oebb.at).

3. Simulation as basis for economically feasible Rail-CPS

The principal idea of deploying trainlets on a *Nebenbahn* is to offer several empty trainlets in each station analogous to a taxi queue. As *Nebenbahnen* are closed, small systems, we can start with a centralized control for dispatching the trainlets between stations. One problem is that *Nebenbahnen* typically have only single-line tracks. Some stations offer two tracks. Thus, one challenge is to come up with load balancing algorithms that guarantee the availability of trainlets at any time, when passengers arrive at any station of the *Nebenbahn*. Automated train control has to assure collision-free two-way traffic on single tracks by utilizing multiple short diverging sections.

We have used discrete event simulation to fine-tune our Rail-CPS concept. In particular, we have to answer the following questions:

- the amount of trainlets required to assure their sufficient availability at any time
- the amount of time that has to be spent for waiting in diverging sections for oncoming traffic
- the mileage required for sending unoccupied trainlets to other stations for load balancing
- the total mileage of trainlets to transport the same amount of passengers compared to traditional trains
- the maximum throughput of passengers on the system

Simulation of a representative *Nebenbahn*. The travel distances of passengers in that particular simulation were based on existing statistics. We assume the availability of short diverging sections at every station and 1.3 passengers per trainlet.

We apply the following straight-forward clearance policy for trainlets: every trainlet gets a driving clearance from the actual position only to the next diverging section, in case no other trainlet is already travelling in the opposite direction on the particular track section. Multiple trainlets can travel on such a section, as long as they share the same direction and obey to a safety margin for breaking. Assuming that a real-time train control system based on radio data transmission is deployed, this can double the throughput of a single track. Such a train control concept would also mean a paradigm shift in rail traffic, as it has a self-organising flavor compared to the traditional centralized scheduling that allows one train per section block.

To avoid collisions, the rule *at least one diverging section between every two trainlets travelling in opposite directions* has to be obeyed too. In other words, a trainlet has to compete with oncoming traffic. This strategy favors high one-way traffic densities, as they are observable in the morning and evening commuting traffic scenarios.

Simulation results. We simulated the *Auto-Bahn* concept for a *Nebenbahn* with a short track with a length of 13 km, an average of 400,000 passengers per year, and 13 stops. With the traditional schedule a passenger has a maximum travel time of 25 minutes. 14 rides are scheduled per day in each direction. The Auto-Bahn needs 70 trainlets to fulfill the travel requests with a maximum waiting time of 10 minutes and an average waiting time of less than 10 seconds. The peak load of travelling trainlets, relative to the total amount of trainlets, was 65%, with an average of 30%.

The waiting time for trainlets in diverging sections for oncoming traffic is stable around 42% with a safety margin of 10 seconds between trainlets for breaks. Without a safety margin it is 37%. Around 20% of all rides have to be spent unoccupied for load balancing. The mileage to transport the same amount of passengers as the train, explodes to a factor of 15, which impressively shows the effectiveness of mass transportation compared to individual, personal traffic.

Nevertheless, we are surprised to find that even with this wasteful concept of just 1.3 passengers per trainlet, we would be able to exceed the known traffic throughput on a single rail track, compared with regular trains travelling on schedules. This indicates that railroads with their current rigid dispatching and control system waste the resource railroad.

With respect to the fact that laser scanners and other sensors, which are required for obstacle recognition, are still too expensive to be used for just 1.3 passengers per trainlet, we set up another simulation with an increased capacity per trainlet of 10 passengers waiting up to 6 minutes once the first passenger entered the trainlet. This still avoids schedules and therefore is significantly more attractive for passengers than trains operating on a static schedule.

The alternative concept reduces the number of required trainlets from 70 to 8 on the simulated *Nebenbahn*. This setup should make autonomous trainlets economically feasible.

5. Summary and implications for (rail) CPS

We are convinced that Cyber Physical Systems could significantly improve the attractiveness of passenger trains and lead to a better use of available railroad capacities. This is especially true for Europe with its dense network of railroads.

Cross-domain improvements. Transforming railroad systems into CPS does not seem to require significant technical innovations. A smart mix of existing technology from areas such as robotics, telematics, radio data transmission and embedded control seems to be sufficient. Nevertheless, it would be helpful to have tool kits available from which specific systems can be quickly composed. In case of an Auto-Bahn CPS, tool kits for obstacle recognition and navigation would be helpful. Such a toolkit would consist of a plug-in software architecture and the hardware sensors and acturators that correspond to the plug-ins. For example, one should be able to quickly assemble a navigation subsystem from a navigation tool kit, depending on the particular precision requirements.

Core (technical) challenges. Again from the viewpoint of an *Auto-Bahn* CPS, we think that mixing a CPS with a traditional system is a challenge. Neverthelss, this will be required for the incremental introduction of CPS. This would also require a mix of centralized and non-centralized control, depending on the particular CPS. In case of the *Auto-Bahn*, the closed systems of *Nebenbahnen* allow a straight-forward first step. We are convinced, that in less than five years, rail CPS based on the *AutoBahn* concept as sketched above can be deployed on existing railroads. This is, for example, not obvious in case of automotive CPS with autonomous vehicles. In addition to that issue, a main obstacle for a fast roll-out of CPS are probably legal hurdles.

References

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