Automatic Train Operation: History and Open Questions

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Abstract: The paper presents the concept of automatic train operation. We give here short description of its functionality and remember some points from its history. There is an overview of various future development as well as proposals for improvement of some existing, especially mainline, solutions. There are presented also some observations from decades of practical use of automatic train operation in the Czech Republic. Selected challenges are presented and discussed.

1 INTRODUCTION

Even long-time used technologies as railway (what could be expected to be already mature) could be further improved. One of the possible improvements what are slowly getting into action (or what is intended to be used in relatively near future) is *Automatic Train Operation* (ATO). It is a technology allowing (under some circumstances) to ride a train. In some cases (at special separated and protected tracks as in underground or airport trains) it could replace the driver, otherwise it could help the driver to fulfil his hard work. It could help to care about speed limits, stopping points, and to some extent also following the timetable.

ATO itself is partitioned into two cooperating systems: one collects necessary data and distributes them to the trains (usually called *trackside*), and the one that could drive and control the trains (or take part on it) using the received data (called *onboard*). The onboard part usually cooperates with *Automatic Train Protection* (ATP; a system that protects the train from some critical situations like going too fast or running through place where it is not allowed) and with train control system.

The trackside part should collect and distribute all the necessary data concerning train ride. They are collected from various systems: track description from asset management, timetables and current data from (often multiple) Traffic Management Systems (TMS) that control traffic within given area.

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ATO can play multiple roles: It can simplify driver's work by taking control over speed, precise stopping, and following the timetable. It can reduce energy consumption by optimizing train speed. It can reduce train and asset maintenance costs by reducing the speedups and braking during the train ride. ATO systems can also handle the door opening and closing.

For its proper use ATO must be able to recognize where the train exactly is, what the limitations of the track are, where are the planned stops, and a lot of other information. There are two basic approaches to equipping train with necessary information:

1. The train is always online and getting changes whenever corresponding TMS collects them.
2. The train is equipped with track description and timetable and potential changes could be handled by informing the driver that could make some adjustments.

Let us make a tour on the prerequisites and history of ATO, its current development and focus on its open questions. We will mention several approaches and compare them.

Structure of the paper is as follows: Overview of principles used for ATO design and how they cooperate are in Sections 2 and 3. Data overview and related procedures are in Sections 4 and 5. Section 6 lists common challenges to be solved by any ATO solutions. Section 7 compares on-line and off-line ATO. Our experience from development and decades of use of ATO are in Section 8. Common requirements of potential ATO systems are collected in Section 9. Section 10 focuses on solution-specific chal-

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lenges. Our proposals and hints are collected in Sections 11 and 12. Finally, Section 13 summarizes the conclusions.

2 BACKGROUND AND HISTORY

2.1 Technical Background

Some actions required for proper ATO functionality are required also for proper functionality of ATP. As safety is for railway more critical requirement than simplification of drivers' work, some of the techniques were developed primarily for ATP.

Such functions cover positioning of the train, encoding speed limits and signals, computing braking curves, handling varying train length, and many others. Many of the problems are complex and interesting tasks also from IT perspective: For example, for train positioning the input data are often taken from various sources with varying quality but the result (where to stop) must be quite precise – the train must stop sooner than at indicated position (before "stop" signal or before end of track). Basic source of linear position (position on the track) is usually taken from odometry (system computing current position from wheel cycling). As the wheels could slip and slide and their size is usually not known with absolute precision, after a while such measurements could differ from reality. It is therefore necessary to detect the precise position using other means and restrict the position error given by odometry. This precise positioning is performed by precise placement of balises (special points detectable by trains) into track. Balises usually work on magnetic or electromagnetic basis.

The balises must be (to some extent) unique – they must be equipped by a code identifying them. It allows the trains to recognize where they are.

Global satellite positioning systems (like GPS, Galileo or GLONASS) are currently not always precise enough to deliver the data according to the needs of ATO. For use in railways the shift of three meters may cause erroneous positioning of the train to parallel tracks. But even parallel tracks could have different speed limits and different positions of signals and platforms.

Satellite positioning is acceptable for lengthwise positioning (where on the given track the train is) especially at local tracks. Precise lateral positioning must be supported by additional systems or by human involvement.

If the train should stop with given precision, the track data must be available with at least slightly better precision.

The railway speed limits are related not only to the train front but also to the train rear – usually it applies what is more restrictive. It is, the train (its driver as well as its ATP and ATO systems) "must know" its length to identify, what are the real speed limits along the track.

The above mentioned techniques and procedures developed for automatic train protection could be often used (after some changes) for the automatic train operation. Some of them have been directly developed for ATO: when an older ATP system, which does not provide localisation information, is used, ATO requires its own source of precise train positioning.

2.2 Highlights from ATO History

First systems helping drivers to stop by the platform were developed in the second half of XX-th century.

The first ATO systems were developed for closed railway systems like metro or special railways. The Victoria Line in London (UK) has been opened with automatic train operation in 1968. The Bay Area Rapid Transit using multiple lines ATO has been opened in 1972. Line C of Prague Metro has been equipped with ATO in 1978.

The first ATO used for classic railway in everyday operation (AVV, *automatické vedení vlaku*) has been introduced in Czech Republic in 1991. It works on many lines (around 3000 km of total approx. 9000 km od Czech Republic railway network length) running on shared tracks with non-ATO trains.

2.3 Current Development

During last years there is a significant development in ATO driven by various projects in various countries. Some systems are based on tight cooperation with single ATP (e.g. ATO over ETCS), others are going to be more open.

There appear first demonstrations or even applications of fully automated (unattended – without driver) classic railway ATO in many countries (Australia, China, Russia, ...). For practical use it makes sense to make them interoperable in larger areas (huge countries or even continents).

Later in this paper we will mention some of the prerequisites of such interoperability.

3 HOW ATO WORKS

As written above, ATO is divided into two basic parts (compare also Fig. 1):

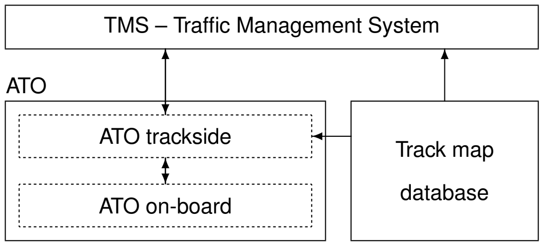

Figure 1: Rough view on ATO and cooperating systems.

1. **Trackside** – collecting and converting data from various sources to the form usable for the second part
2. **Onboard** – performs following actions:
   (a) positioning the train;
   (b) computing dynamic speed profile according track description, signals, additional restrictions, train attributes, current conditions, and timetable;
   (c) traction / braking control;

Trackside part of ATO must be able to cooperate with other trackside systems – especially with TMS that have timetables and asset management that keeping track description up-to-date.

Building trackside part is a task of infrastructure manager, whereas equipping trains with the on-board part must be done (ordered and paid) by the vehicle owner. As many trains are going across borders between areas under control of different infrastructure managers and within areas of individual infrastructure managers There are several projects trying to make the necessary parts interoperable across several countries – equipping tracks and vehicles by ETCS. The proposed standardized architecture is – with respect to work of ATO WP in Shift2Rail published e.g. in (Buurmans, 2019) or in (X2Rail-1, 2017) – in a simplified form captured in Fig. 2. Subsets are specification documents of the ERTMS/ETCS system used in the European Technical Specifications for Interoperability of the Railway System.

4 NECESSARY DATA

Complexity of the task can be derived from the data that are necessary. The following simplified list contains data for both (on-line and off-line) ATO versions:

- Track description
  - speed limits according train class (position, value, and front/rear validity);
  - gradients (value, position);

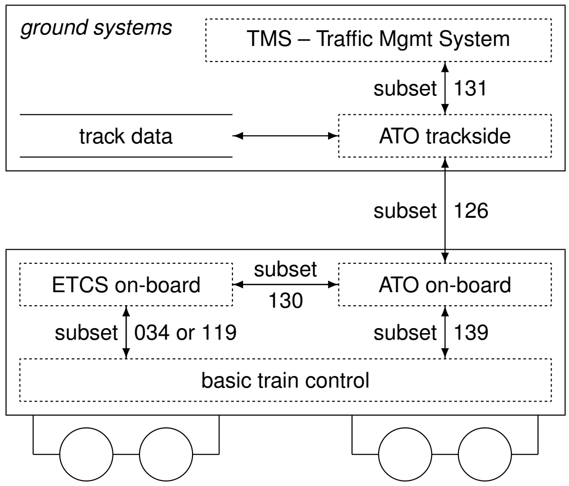

Figure 2: Cooperation of ATO with related services and their specification in subsets.

  - platforms (positions, length, train alignment);
  - position of signals (if not transmitted from ATP);
- timetable
  - times for planned stops
  - times for passing points (time navigation)
- other limitations
  - power limits
  - axle load limits
  - ...

5 HANDLING DATA CHANGES

The data could change even when the train is on the track – additional limits could appear, the train will take other path, etc. The issue is, how the train can cope with it.

The data update could be sent to the train only if it is available online. When the train is not connected to the network, other approach must be used.

5.1 Connected Train

European Union Agency for Railways (ERA[2]) plans to introduce a standardized communication between TMS and ATO and between ATO trackside and onboard parts based on the work performed by the companies organised in Shift2Rail[3], UNISIG[4] and EUG[5].

[2] https://www.era.europa.eu/
[3] https://shift2rail.org/
[4] http://www.ertms.net/?page_id=50
[5] https://ertms.be/

5.2 Off-line Train

The selection of different path (using other track than planned but still going through the same stations) must be always taken into account: the train speed must reflect the current strongest speed restriction. In some cases the selected routes could be recognized from signalling: straight track usually does not restrict the speed (and could be signalized by ”free”), whereas siding often limits the speed (and could be therefore signalized by lower speed limit). The information about the active signal could be transferred through ATP.

6 COMMON CHALLENGES

The way the data are reaching the train does not influence some of the technical challenges that must be solved anyway. It covers train positioning, speed limits, braking curves, acceleration, and many others.

Many of the challenges have been already discussed in literature (and, of course, tested in practice). Let us mention at least some of them.

6.1 Train Positioning

One of the hardest challenges for ATO is precise, safe, and reliable train positioning. Although trains are moving on rails (and their positions are known) it is still not easy to position the train precisely enough: GNSS (global navigation satellite systems) localisation error may be greater than the Also the positioning on the track is often required to be more precise than the GNSS-based position could give.

One can say that automatic train protection (ATP) systems must have precise enough positioning. They can determine the track. But they have different approach to linear positioning: For an ATP system the error could be asymmetric – if it stops several (probably also several dozens) meters sooner than necessary, it is still good enough. But it is not allowed to stop even a bit later.

ATO has other requirements on train positioning: it needs to stop not too late but also not too soon – e.g. not to miss the platform or not to speed up too soon.

6.2 Speed Limits

In some cases the speed limits concern front of the train, in other cases its rear. In most cases it holds for the more restrictive case: when the speed limit is getting more restrictive, it must be fulfilled by the train front (front of leading vehicle), whereas speeding up must be usually done with respect to the rear of the train. Exceptions exist and are marked by special signs allowing immediate speed up.

Some speed limits are fixed for a long time (typically the ones related to the physical parameters of the track). These parameters could be distributed to the trains on-line as well as off-line.

Temporary speed restrictions and speed restrictions given by route setting are of dynamic nature and need to be updated immediately. They must be transferred on-line or entered by operator (driver). For (automatic) driving it is only important whether the data are available in time. From the ATO perspective it is not important how the data get into the system.

As mentioned above, it is important that the train must reliably know its length. Although it could look easy, it is not so. Trains could be composed not only from new vehicles but also from older ones – even decades old. Such vehicles need not be necessarily equipped by the most current electronics and software.

6.3 Acceleration and Braking Curve

If we know (as described above) the speed limits, we should also drive so that we obey them. There are many parameters that should be taken into account:

- gradients
- tunnels and their diameter/tightness
- adhesion
- available power output and its limitation
- braking type and mode
- ...

The above parameters could influence the train individually as well as in combination. Some of the parameters are not known precisely – so, the control must therefore take into account also the current behaviour of the train.

7 DIFFERENCES

It appears that on-line and off-line ATO systems can share most algorithms – computations like positioning, speed profiles, timetable matching, braking, or door opening appear to be the same. The differences are in availability of information about surrounding traffic, and real route settings. On-line ATO can have all such information – if the connection with its trackside part will work as expected and everywhere where needed.

The main difference comes when the systems come under stress: On-line systems could take advantages from updates if they are prepared and sent in time by trackside (or the TMS behind). Off-line systems have only pre-loaded data. It is therefore meaningful to load them with full maps and equip the track so that they could quickly recognize where the route leads (to which speed profile and potential stops).

On-line ATO can result in more efficient ride of the trains (as they have more up-to-date and more precise data) – but only where the data are available and in time. Off-line ATO is cheaper and can be used even when the surrounding traffic data is not available.

8 EXPERIENCE FROM AVV

8.1 A few Gossips from AVV History

Automated Train Operation/Control (In Czech: *Automatické vedení vlaku* (AVV); (Myslivec et al., 1998; Lieskovsky and Myslivec, 2011)) is a system installed on hundreds of vehicles and used in practice for many years (in commercial operation since 1991, tests since half of 1960's). Its basics have been developed decades ago. It has been therefore limited to preloaded data available on board (at those times no GSM-R or related technology has been available).

The dependency on preloaded on-board data led to the graph-like track description. The graph contains all tracks equipped with AVV-compatible balises. The system can be therefore used everywhere where there are necessary data available and where it is possible to position precisely the train. The system is therefore robust to any change of the train path within this graph. It the train is sent to some part of the track where no information is available, it switches to control by the driver. The system always takes into account all (known) possible paths.

8.2 Cooperation of AVV with ATP

The AVV system reads the signals from national Class B ATP system (compare (Lieskovský et al., 2006)) and is capable to utilise data from onboard ETCS if available (see (Lieskovsky and Myslivec, 2011)). Even if no ATP is available, AVV can work alone and can prevent some critical situations (can slow down or stop the train if necessary).

8.3 AVV Approach to Data

The system is able to work without connectivity to TMS On the other hand, it is limited to the areas for whose it is equipped with corresponding maps. The system is designed so that if a driver has some useful information (s)he can enter the data relatively easily.

9 COMMON REQUIREMENTS

It is likely, and the available documents prove, that all ATO systems need some basic information. It covers information about speed limit start and end positions, their validity for beginning or end of the train; platforms and their positions; stopping points (their positions and required train alignment there); and train timetable. There should be also information identifying stations (to provide information about them to the passengers), optionality of the stop (to induce its potential request). Additionally, there should be available also some safety requirements (not to stop on some places where it is not possible to rescue people from the train).

If possible, it can be advantageous if there is information about current conditions around the train like signals or information about other trains (e.g. if there is a slow train ahead of given train, it could be reasonable to slow down a bit); sometimes it could be advantageous to speed up to allow smooth train crossing on a more appropriate place.

The data could be stored efficiently. The detailed track description covering haul between Praha and Kolín (62 km distance, multiple stations, about 320 km of single track, single direction line) have been stored in a 3KB piece of EPROM.

10 DIVERGING REQUIREMENTS

Various ATO systems could require different additional information. It can cover position and radius of curves, some could require also their direction (in other cases only modified train resistance could be enough). Similarly, some systems can take advantage from information about tunnels and bridges and their parameters.

As it seems to be advantageous to have this information as in these places, the train running resistance really is higher than the one in straight track in open country, the fact is that the running resistance provided by vehicle manufacturer is usually higher than reality (not to be a problem to verify it during the tests) and after adding this additional component, the expected running resistance goes more away from reality... Finally, there exists a component that is not possible to take into computations: wind. Its asset to running resistance is much higher than the one of tunnels, bridges or curves.

In some countries it is allowed to stop at a long enough platform only, in some countries there is sometimes allowed to stop at a short platform and open appropriate doors only. Support for it could be also recognized as useful in some cases only (e.g. some infrastructure managers could require it and some do not want to care about).

It could be useful to distinguish how the doors are opened: at some stations they could be opened automatically, on other stations they could be only unlocked for opening on demand.

11 THE PROPOSAL

11.1 Approach to ATO

We propose to treat ATO as a general service with preference of robustness over implementation simplicity.

We suppose that customers could benefit from having ATO as able to work on ETCS- as well as national ATP-equipped infrastructure. Having information about the planned path with adjacent tracks (i.e. to have the information of the track not only as a line but as a general graph) could make the system more robust to the data failures.

ATO solutions capable to operate on both interoperable (ETCS) and non- interoperable lines can benefit from the data from various ATPs. It can extend applicability of the ATO technology with all its advantages to significantly more tracks and trains. Measurements published in (Šula, 1990) and mentioned again in (Jackson, 2017) has shown that AVV has saved 10–30% of energy as well as improving timetable. Can we say that these advantages will not be allowed on local tracks?

11.2 On-line vs. Off-line

We suppose that the modern ATO systems should be built so that they can work in both environments: online as well as off-line. It makes sense to build the ATO system so that it could be used on-line as well as off-line and with any ATP fulfilling some reasonable minimal requirements. It also makes sense to define minimal set of functions necessary for driving the train by ATO. Such interface could then be used by ATO without necessity to re-certificate the train control in all countries.

11.3 Opportunity not to Collect Unused Data

Some data are in some countries already not collected. As they are typically not used there, it could be enough to set up generally some default value and do not mention it in all track-describing datagrams. But it requires the applicability of country- or area-predefined values and more variable data format.

On the other hand, if some data are not available, it could be better to have an opportunity to support only partial description of the track. If the on-board ATO can use the available data, OK, if not, let it (temporarily) switch to manual control over the train.

11.4 ATO–train Interface

The communication between ATO and vehicle there must be at least:

- request on traction / brake;
- backward information on the successful use of traction / brake;
- other parameters of the train not processed by ATP (often ETCS) – like weight, overall power, or traction limits.

11.5 ATO–ATP Interface

The data transfer between ATP and ATO contains the data that is ATP able to provide. In the case of ETCS it is especially:

- static speed profile;
- braking and other parameters of the train (e.g. train length) to synchronize the values between ETCS and ATO; ATO is therefore able to compute the same braking curve as ETCS (and anticipate the braking activities of ETCS);
- localization data (identification of the position of the train on the track / network);
- last but not least, data from ATO for displaying on the ETCS display. It appears to be reasonable (and about 20 years of practice with AVV shows that it is gracefully accepted by the drivers) to provide extra display with complex information about the situation on the track in front of the train and about plans of the ATO itself.

11.6 Data for ATO

The data for ATO system can be divided into following groups:

1. **Static** (changes usually after several years or decades) – track description, speed limits, positions of platforms, points of interest, stopping alignments, etc.
2. **Semi-static** (could change several times a year) – published timetable (train routes, stops, departure and arrival times, ...)
3. **Varying** (usually change in weeks or months) – temporary train path changes (e.g. due reconstruction of the track), temporary speed restrictions, ...
4. **Dynamic** (could change during the train run) – selected routes, time restrictions (the train should be there not sooner than t_a and not later than t_b).

12 SEMI-OPEN QUESTIONS

The world of ATO faces many questions. Some of them have been handled in the past but current solvers must try it again. Let us mention and formulate some of them and give some hint according the first try.

12.1 Optimal Human–Machine Cooperation

For the ATO community it is not clear what the optimal way of human-machine (driver–ATO) cooperation is. Some authors (compare e.g. (Bienfait et al., 2012)) claim that there must be clear cut between full control by machine (ATO) and full control by the driver. Others (compare e.g. (Lieskovsky and Myslivec, 2011)) propose to combine advantages of both worlds. Practical combination is probably more complicated to implement (and, what is harder, requires deep understanding of the designers/developers of the interface to train driving) but appears to be less restrictive and more flexible.

Let us formulate it using following parable: The driver is smart and experienced enough to optimize train driving based on his past experience and has a better access and understanding of specific operational rules and limitations. The machine could be better than the driver as it could have more detailed or more precise specific data regarding train drive and due to fast computation algorithms can provide specific action more precise and faster. Symbiotic work of the machine driver and computer can take advantage from both worlds: from precise computation over lots of date and from experience and understanding.

12.2 Data Inconsistency Handling

As ATO as a whole collects for its proper work information from many systems and as (according current knowledge from physics) the speed of a signal is limited, it could happen that the data from various sources are not synchronized. The question is, whether we should expect that the data synchronization is the task of all connected systems (especially TMS) as it is expected in current developments in ATO standardization in Europe or should there be mechanisms in data distribution and exchange allowing to recognize possible inconsistencies.

It seems that it is safer to be prepared for situations where something went wrong. We propose to sacrifice small part of the system data throughput for mechanisms allowing recognizing of potential issues just to allow reasonable reaction.

12.3 Communication to Driver

What is the optimal extent of the information that ATO should share with the driver? Should it be minimized (not to disturb the driver) and safe a display or should there be complex information on the situation ahead and on the plans of ATO? The currently proposed solution in AoE (one line of text is enough) is derived from the fact that the ATO should not cooperate with driver but drive the train alone (until the train stops or until the driver takes control over the train). The approach used in AVV (compare Figs. 3 and 4) prefers providing complex information the driver by ATO with all necessary data (like how far is the next speed limit, what is the next signal and where it is, or what is the next stop).

This picture was created upon of opinions and notes of approximately 100 drivers, which took part in the first year of real computer-based ATO operation on Czech Railways in 1991. In contrary to other approaches, it comes from real, not simulated operation, and from real drivers, who were responsible for safety and punctuality of real trains. After implementing changes, this picture remains stable for almost 30 years of everyday use.

13 CONCLUSIONS

We have described automatic train operation as useful intelligent system facing many interesting challenges and issues. It has already shown its practical advantages – compare its use in underground in many cities, in several airport local trains, as well as in regular use in standard railway (AVV).

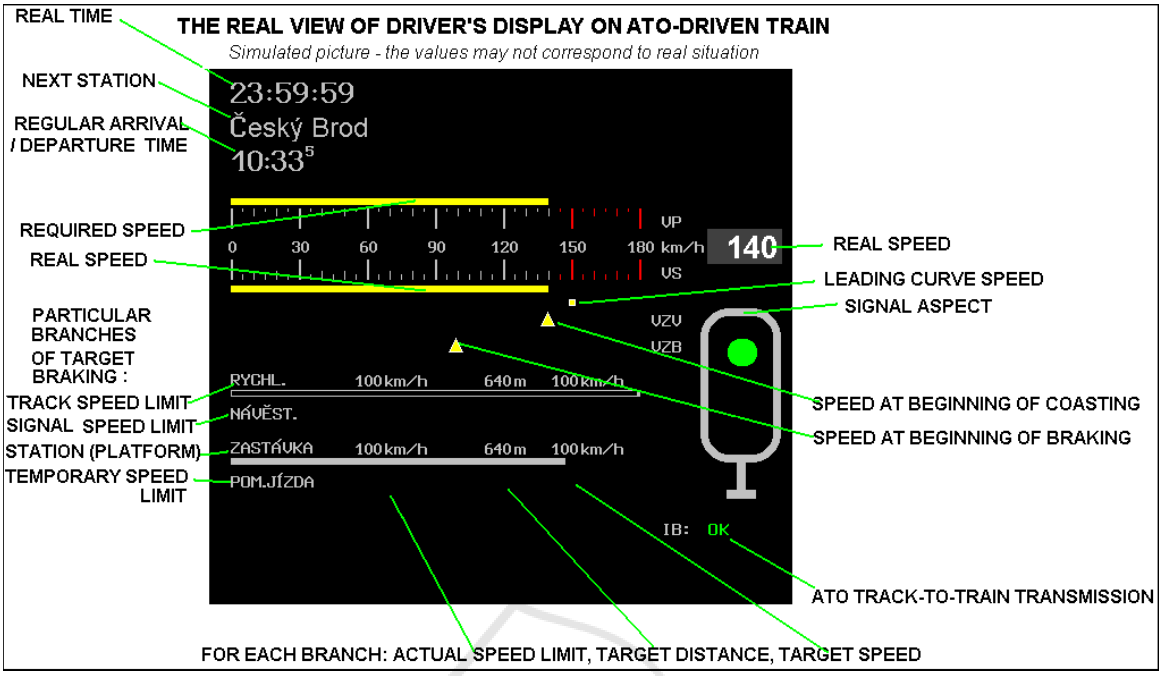

Figure 3: AVV Display Explained.

Figure 4: Diagnostic and AVV Displays.

Several challenges have been introduced and discussed as well as current developments in the area. It has been observed that a significant group of current developers tries to re-solve identified challenges that have been already put and answered in the past. We have described them and have tried to explain why the questions have been answered so.

Currently the practical task in the ATO is to equip the railway with the necessary equipment (balises), to equip the trains with corresponding equipment, to collect the necessary data and to connect the ATO to other trackside systems. It appears that many questions of ATO concept and implementation (some of them were mentioned here) could be answered only if the corresponding people will get their own experience with ATO development, testing, and use.

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