Generating and optimizing strategies for the migration of the European Train Control System

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Abstract

The growing interconnection of the European Union and the increase of international traffic oppose new challenges to railways. The EU has decided to improve the situation by introducing the European Train Control System (ETCS) on corridors to achieve cross boarder interoperability. Therefore, an optimized migration strategy is needed. The approach presented in this paper examines the whole corridor with its details and the dependencies with the rolling stock. It avoids planning mistakes, guarantees cost optimized strategies, and eases adoption to changed parameters. To generate all possible migration strategies, the corridor has to be modelled in detail. Therefore, it is divided into homogenous sections. The fleet planning is extracted from the rolling stock and the traffic. It is applied on the corresponding sections. Based on this, requirements and dependencies are derived. This is especially important if deadlines have to be considered that determine the state of equipment to a specific point in time. Due to the complexity arising from the constraints and interdependencies, the generation of strategies is carried out automatically. The tool built upon the approach also delivers a rough schedule for the project management. Consequences of changes along the planning constraints can easily be computed, e.g. rescheduled deadlines. Subsequently, the strategies are evaluated and optimized. For a comprehensive cost-benefit analysis, track performance can now be taken into account. Furthermore, different perspectives of the optimization can be compared. The method delivers comprehensive results that would be a good and transparent baseline for negotiations among the stakeholders to find a mutually agreed strategy.

Keywords: ETCS, migration, strategy, optimization, decision support, automatic train protection, ATP, railway infrastructure, rolling stock.

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1 Introduction

The growing interconnection of the European countries demands high investments in the automatic train protection (ATP) technology. Due to the ongoing globalisation, mobility of goods and people gains higher importance. Historically, the railway has been bound to national borders. Thus, independent ATP systems have developed in every nation. A standardised system would create interoperability and also end the diversity of the European ATP market. Barriers for competitors to enter the railway market would be lowered. To reach these goals, the EU has decided to introduce the European Train Control System (ETCS). This takes place first along trans-European corridors of interoperability that connect important industrial centres and regions [1].

This change of technology has to take place without interrupting the railway operations. Such a process is described as a technology migration. Therefore, it is necessary to proceed with a highly coordinated migration strategy and to commit to technical standards [2]. In addition, safety and performance have to be extended or maintained, resulting costs have to be minimized and benefit has to be gained quickly.

The existing technological and operational surrounding is well known and defined. ETCS itself is specified for the most part and already in a testing and operation phase. So this paper does not deal with the actual choice of technology, but the choice of the migration strategy.

The main challenge of the migration is the huge number of relevant parameters, constraints and dependencies. The migration of vehicles and infrastructure has to be coordinated and optimized. Furthermore, the complexity is increased by the long life cycles of railway technology. On the European and the national level a heterogeneous picture of systems emerged over time. This leads to difficulties considering the various interfaces. Thus, investments beyond ETCS may be required.

The presented method takes these constraints and parameters into account. From this baseline, migration strategies are developed and evaluated. Fig. 1 gives a brief overview of the method which is as well implemented in a tool.

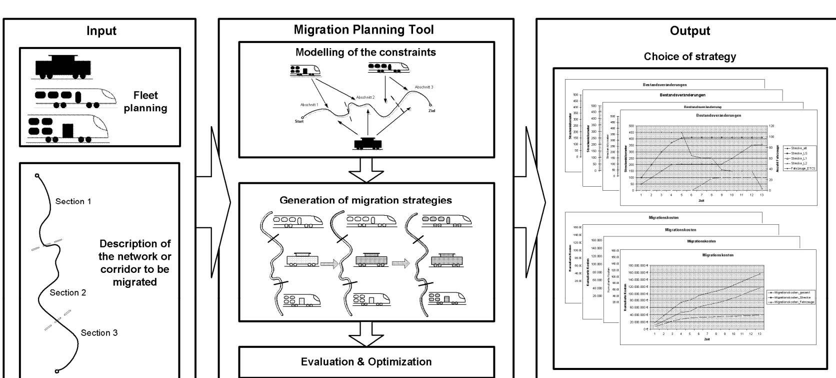

Figure 1: Overview of the method.

2 Phases of the migration

The planning of the ETCS migration can be divided into three levels. The highest, strategic level contains the coordination of the EU, the railway companies and industry. Here the overall strategy as well as the technological standard is committed. On the tactical level beneath, the migration on each trans-European corridor as well as in each participating country is planned [3]. The detailed project management of each participating company can be seen as the lowest, operational level. It has to be ensured, that the levels are consistent with each other.

Furthermore, the planning of the migration of ATP technology can be split up into four phases [4]:

- System modelling
- System selection
- Generating migration strategies
- Evaluation of the migration strategies

In this paper, the migration is handled on a tactical and operational level with a specified system i.e. ETCS. The following chapters show how the modelling and the generation of strategies are carried out. Beforehand, existing constraints have to be defined.

3 Technical and operational constraints

The first step for the method is the collection of constraints and parameters. In this context, constraints are factors that cannot be changed during the migration. On the contraire, the choice of parameters is free to a certain extent.

For a better distinction between old and new ATP according to [1], all ATP systems that are compatible with ETCS shall be called Class A systems; national ATP systems incompatible to ETCS are called Class B systems.

3.1 Infrastructure

The key problem of the migration of ATP systems is the incompatibility of Class A and Class B systems, which concerns onboard and line side units as well as legacy interlockings and ETCS in general. To meet the different requirements of train lines across Europe, three so called Application Levels exist.

If ETCS Level 1 is installed, the legacy infrastructure elements, i.e. signals, train detection and interlockings remain at the line side. Because of the stationary signals, ETCS Level 1 is defined as a discrete ATP. The valid signalling and speed limit is displayed at the driver’s cab. This version is called Full Supervision (FS). To reduce the engineering costs, there is also the possibility to omit the signalling at the driver’s cab and the permanent speed surveillance. This version is called Limited Supervision (LS). It keeps the advantage of technical compatibility but requires the train driver know the national body of rules and regulations.

With ETCS Level 2 applied, no line side signalling is needed anymore. So the trackside investments and maintenance costs can be reduced. Therefore, every train using the track section has to be equipped with ETCS. If there are any trains solely with Class B systems onboard, the line side signalling has to be kept up. Apart from that, the line side train detection cannot be removed. Electronic interlockings are required. If there is an interlocking of any other type at the line side, it has to be replaced or new interfaces have to be installed [5].

The difference between ETCS Level 2 and ETCS Level 3 is the way of the train detection. At Level 3, it works by a satellite positioning system, fixed repositioning balises, and an onboard train integrity determination. This gives the opportunity to save even more infrastructure and thus reduce the maintenance costs. So far, there is no train integrity determination existing for freight trains. ETCS Level 3 is a moving block system. So the safety clearance between following trains is not made sure with fixed blocks. This increases the line's performance.

The rules and regulations, e.g. in Germany [6], distinguish between the permitted types of ATP systems depending on the line's maximum speed. Discrete train control systems are only allowed up to a speed of 160 km/h. On lines with a higher speed, continuous train control systems have to be used. Thus, high speed trains have to be migrated either with ETCS Level 2 or ETCS Level 3. Lines solely used by conventional or freight trains can be equipped with ETCS Level 1.

In order to derive the requirements for the new system from the train operations, the corridor is divided in homogenous sections. This shall simplify the resulting model. Thus, homogenous requirements from the traffic can be assigned. These requirements could be for example the desired number of trains per day or the maximum speed [7]. It also seems useful to divide the corridor by countries. This delivers the installed Class B systems as well as the national body of rules and regulations on the line sections. Furthermore, every train that crosses a border can be marked as international. This way the coordination of all involved parties can be assured.

3.2 Rolling stock

The key question about the rolling stock strategy is whether the vehicles shall be used in open loops on the whole railway network or on closed lines. This mainly determines the number of vehicles to be migrated in each step. Therefore, it mainly influences the size of the pools in which the vehicles are put together. In the case of closed lines, each line would represent a vehicle pool [8]. If the vehicles are used in open loops on the whole network or huge parts of it, the decision about how to define the vehicle pools is more complex. The first distinction should be made according to the vehicle series. If each series has an area in the network which it is preferably used on, the definition of the vehicle pools can be made according to it. There would only be little changes in the dispatching processes. If there are no preferred areas for the series, either huge changes in the dispatching processes have to take place to assign the series to defined areas, or the migration strategy will be less adjustable and effective i.e.

more expensive, because the strategies of the infrastructure and the rolling stock cannot be adapted to each other very well. Some earnings of the migration e.g. the shutdown of the legacy Class B system or the reduction of onboard Class B systems will probably take place later.

It has also to be decided if existing vehicles shall be equipped with ETCS or if new vehicles have to be purchased. The decision depends on the life span, the technical constraints and the resulting costs for each vehicle.

4 Modelling of the corridor or network to be migrated

A modelled corridor or rail network consists of one or more line sections and one or more vehicle pools to include the traffic. The vehicle pools are assigned to the line sections to match the flow of traffic. Fig. 2 shows the class diagram of a corridor or rail network. As the traffic should not change along a line section, it could be necessary to split up the line sections in even more detailed elements. Each section or vehicle pool is defined according to the foregoing analysis of constraints and parameters. Additionally, it is important to regard how many kilometres and vehicles per year can be equipped with ETCS, i.e. Equipment_Capacity, and how quick the Class B system can be taken off the track, i.e. Dissolving_Capacity. It has a major effect on the resulting strategies.

5 Generation of migration strategies

A strategy in this context shall be defined as a combination of a goal to be achieved and a path towards this goal. All possible strategies form the strategic scope. The optimal migration strategy is part of the strategic scope.

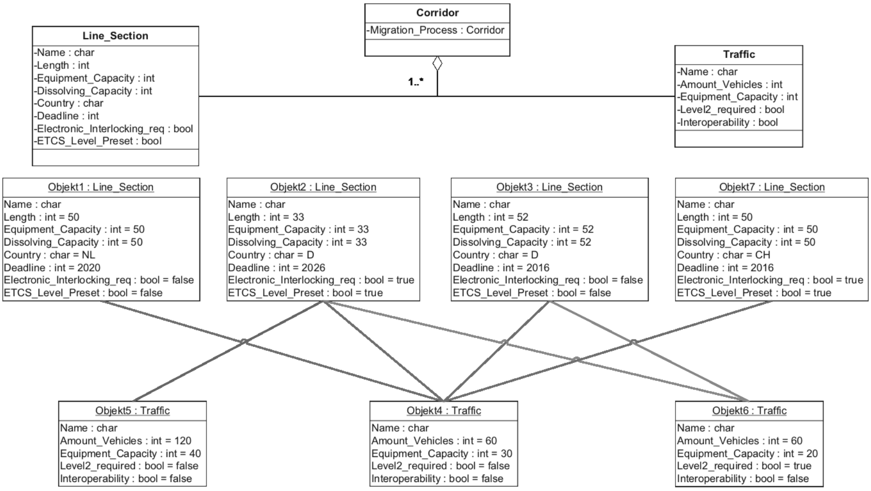

Figure 2: Example of a modelled corridor.

5.1 Migration goals

The definition of the sections of the corridor and the related traffic describes the initial situation of the migration. The next step is to derive the scope of migration goals. Those which do not meet the requirements of the traffic cannot be part of resulting migration strategy. Hence, each allowed migration goal on each line section has to meet the highest requirements of the related traffic. It also has to be regarded whether the Class B systems stay operational or not.

Additionally, the ETCS Level to be deployed can be chosen as a preset. Depending on the characteristics of the corridor, this can be a huge simplification of the resulting model.

5.2 Migration paths

For the migration of ETCS on a line section, three basic migration paths exist [9], each causing different costs. They coordinate the migration of the infrastructure and the vehicles and ensure that the railway stays in operation. This can only be guaranteed by equipping either the line side or the vehicles with Class A and Class B systems in parallel. To speed up the migration, the line side and the vehicles can be equipped with ETCS simultaneously, see fig. 3.

5.3 Examination of the strategic scope

The strategic scope in which the migration strategy shall be optimized is defined by the number of migration goals and migration paths. In addition, the order in which the line sections are migrated has to be chosen. This yields the number of possible strategies N_{total} as follows, with N_{order} as the number of strategies arising from the combinatory order of migration, $N_{opt.section}$ as the amount of strategic options per line section, $N_{options}$ as the total number of options derived from the line sections, s as the number of line sections, g as the number of migration goals, and p as the number of migration paths:

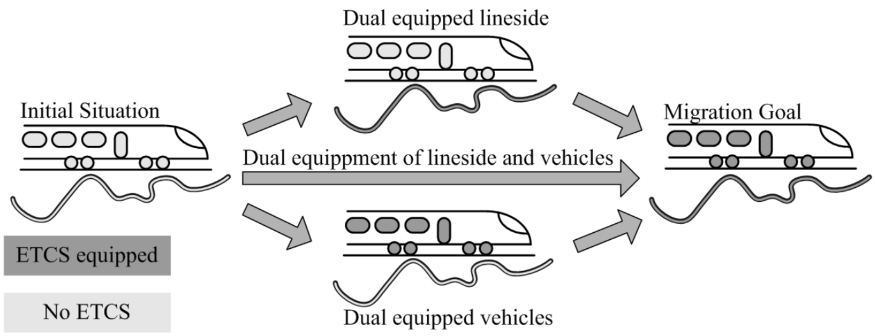

Figure 3: Migration paths.

$$
\begin{aligned}
&N_{total} = \frac{(s-1)!}{2}(g*p)^s = N_{order} * N_{options}, \\
&N_{order} = \frac{(s-1)!}{2}, \\
&N_{options} = (g*p)^s, \\
&N_{opt.section} = g*p \Rightarrow N_{options} = (N_{opt.section})^s.
\end{aligned} \tag{1}
$$

Due to the fact that this analysis of migration strategies takes place on an operational level, the order of the migration of the line sections cannot be influenced anymore. It is already determined by political decisions, set deadlines for the construction of new sections, or set dates of the shutdown of legacy Class B systems. If there should be any scope s_{order} left at this stage of the planning, it comes down to only a few scenarios $N_{red.order}$ to be compared. With eqn (1), this leads to the following example:

$$
\begin{aligned}
&1 \le s_{order} \le 5 \Rightarrow 1 \le N_{red.order} \le 12, \\
&N_{red.oder} \le N_{order}.
\end{aligned} \tag{2}
$$

Thus, according to eqns (1) and (2) the number of possible migration strategies mainly depends on $N_{options}$, i.e. the number of options per line section and the number of line sections. Fig. 4 shows as an example, how the amount of strategies quickly reaches $N_{options} > 10^{30}$. It is not reasonable to generate and evaluate all of these strategies.

Thus, the strategic scope has to be reduced in a way that it allows to compute all of the possible migration strategies. This is achieved by regarding realistic

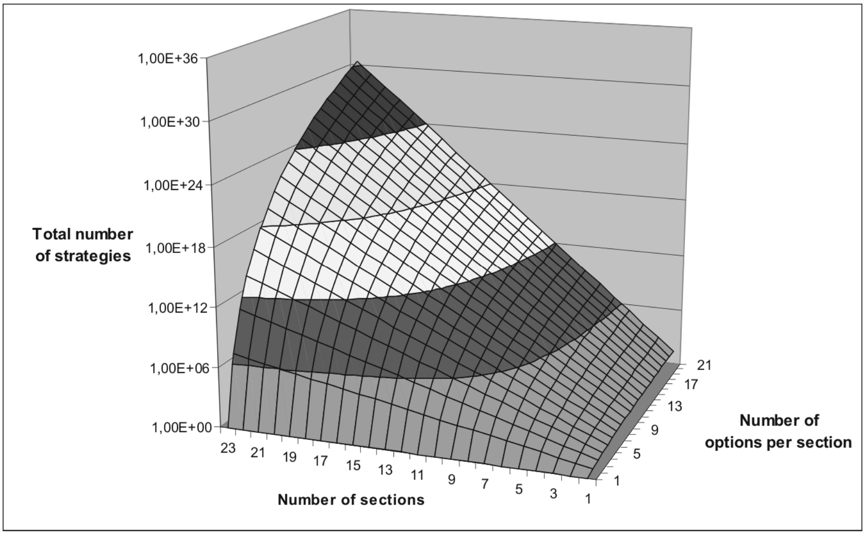

Figure 4: Number of possible migration strategies.

planning constraints. These constraints are e.g. the fixed choice of an ETCS Level to be equipped, whether the Class B system stays in operation or not, and if some of the migration paths can be excluded for a line section or vehicle pool. In eqn (1), these considerations reduce g and p and therefore deliver a reduced $N_{red.opt.section}$:

$$
\begin{aligned}
& g * p = N_{opt.section} \geq N_{red.opt.section} = g_{red.} * p_{red.}, \\
& g_{red.} \leq g, \\
& p_{red.} \leq p.
\end{aligned}
\tag{3}
$$

Due to the fact that a migration goal which results in changing ETCS Level every few kilometres would not be accepted, further simplifications can be found. Some line sections might be re-combined to a number of s_{red} clusters equipped with homogenous ETCS Levels for a given migration goal. Together with eqn (3), this leads to a reduced amount of options $N_{red.options}$:

$$
\begin{aligned}
& (N_{opt.section})^{s} = N_{options} \geq N_{red.options} = (N_{red.opt.section})^{s_{red}}, \\
& s_{red} \leq s.
\end{aligned}
\tag{4}
$$

The assumptions of eqns (1), (2), and (4) lead to the following result for a reduced strategic scope $N_{red.total}$:

$$
N_{red.options} * N_{red.order} = N_{red.total} \leq N_{total} = N_{options} * N_{order}. \tag{5}
$$

Although the strategic scope has been reduced, e.g. to $N_{red.total} < 10^8$, it still delivers reliable results due to regarding realistic planning constraints. The makes it possible to compute all migration strategies. Therefore, a very good baseline the choice and optimization of the migration is gained.

To handle the found strategies properly, the strategic scope is saved as a Petri-net (fig. 5). Starting from the initial situation, different paths to migration goals

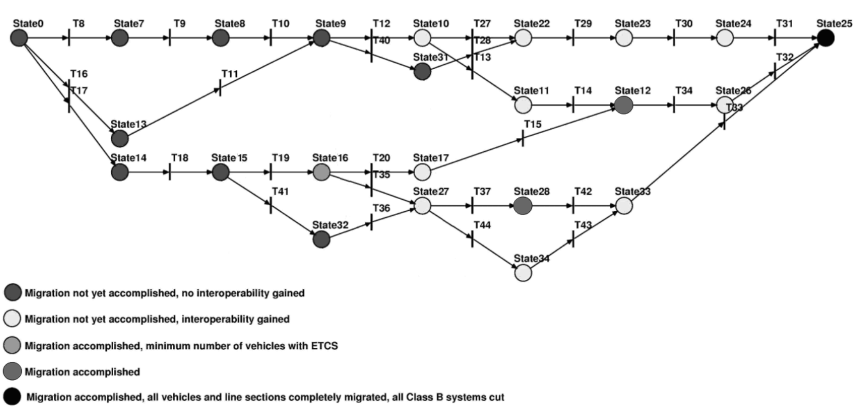

Figure 5: Example of the strategic scope.

are shown. Each combination of a path and a goal for the migration forms a strategy to be evaluated. The states within the Petri-net describe the status of the whole corridor or rail network at a specific point in time. The transitions between the states symbolize the activities carried out during a migration strategy.

The states have been put into different categories. This eases the evaluation and optimization of the strategies. First, it is distinguished between states in which the migration is accomplished and such where the migration has not been finished and interoperability has not been achieved yet. It is also taken into account, if interoperability already exists, but the migration process is not yet accomplished. Finished migration processes could be separated into three different categories. The first category is characterised by a minimum of ETCS equipped vehicles, i.e. a minimum of investment. In the second category, all line sections and vehicles only use ETCS, i.e. all Class B systems have been removed. The last category consists of states with an accomplished migration that cannot be put in one of the foregoing categories.

6 Evaluation and optimization of migration strategies

The generation of the migration strategies delivers the changes of the examined assets over time. For the infrastructure, the point in time of the equipment of each line section is known as well as the number and type of elements required doing so. Due to that, differences between ETCS Levels are regarded in detail. The vehicle pools are treated equally. The amount of vehicles for each pool is considered as well as the point in time of the retrofitting with ETCS or replacement of legacy vehicles with new ETCS vehicles. The following figures show three example strategies, derived from the corridor modelled in fig. 2.

The first example in fig. 6 shows the strategy with the least investments, i.e. the minimum amount of vehicles is equipped with ETCS. The Class B systems stay operational and the deployed ETCS Levels match, but do not exceed the requirements.

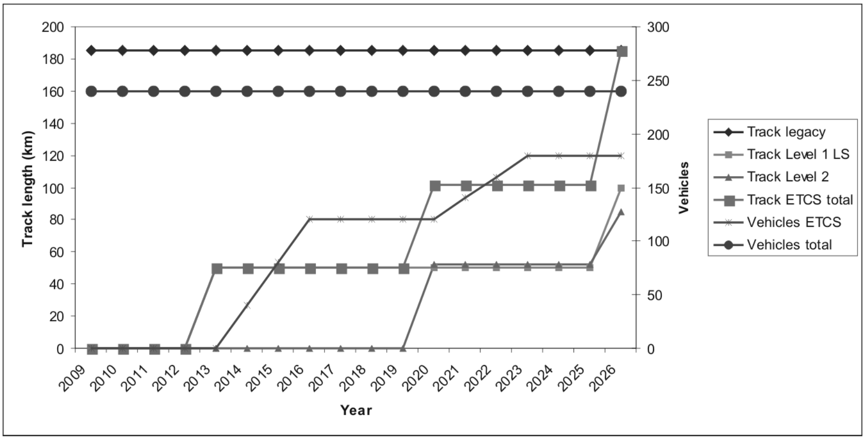

Figure 6: Migration strategy with minimum investment.

The second example, shown in fig. 7, is a strategy with solely ETCS in operation after the migration. Therefore, all vehicles have to be equipped with ETCS, all line sections operate with ETCS Level 2, and the Class B systems are removed. This strategy could lead to a higher line performance.

The last example in fig. 8 shows a possible compromise between performance and investments. All sections are equipped with ETCS Level 2. The Class B systems only stay operational on those sections, where parts of the assigned rolling stock do not require interoperability. This way, the investments in the equipment of vehicles are minimized.

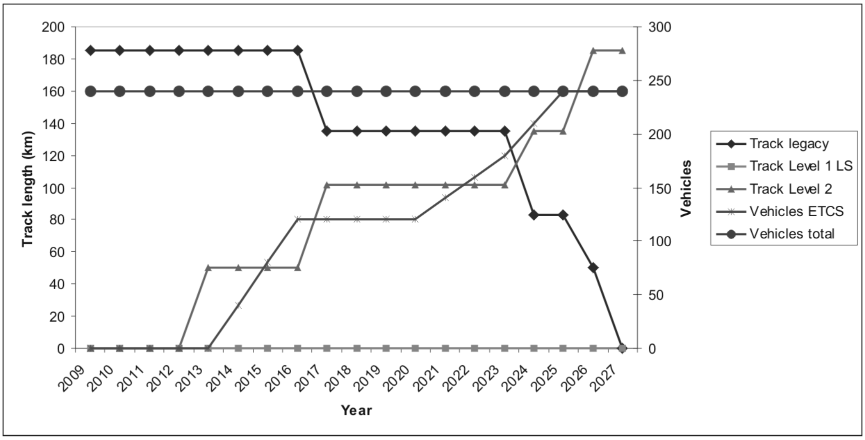

Figure 7: Migration strategy with complete replacement of Class B systems.

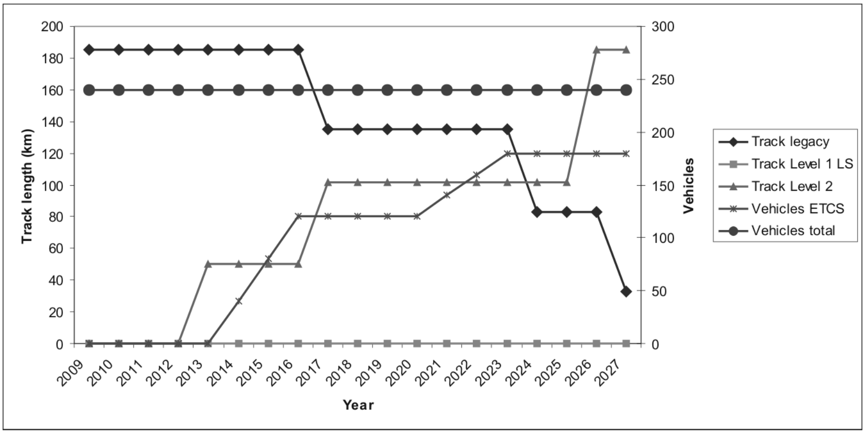

Figure 8: Migration strategy with compromise between performance and investment.

From this baseline, a cost driver is assigned to each asset and element. Additionally, gained value or income can be taken into account, e.g. if the equipment of several line sections leads to new train connections or shorter travel times. This yields the possibility to derive different performance figures, like the net present value, life cycle costs, or migration costs.

For each strategy, the critical path is identified. So, each activity of the strategy can be started as late as possible and as early as required. This leads to a cost optimization of the strategies. For each migration goal the optimal path can be found by comparison of all paths leading to that goal. Depending on the chosen performance figure, this could be e.g. the one with the lowest migration costs or the highest net present value.

Thus, at his stage of the optimization, only the migration goals have to be compared. Fig. 9 shows how the investments of the foregoing examples relate to each other. Now it is possible to take more criteria into account, e.g. to evaluate whether an increased line performance pays off or not.

Due to the automatic generation, evaluation, and optimization of the migration strategies, consequences of changes along the planning constraints can be computed quickly. For example, if the deadline of the equipment of a line section is rescheduled, this might have a huge effect on the equipment of vehicles. This could be useful either to adapt to the changes, or to negotiate about the rescheduling.

In addition, different perspectives of the optimization can be compared, i.e. the infrastructure, the vehicle, and the integrated point of view. The best strategy for the infrastructure side is not necessarily the best for the vehicle side. The knowledge about these strategic options would be a good and transparent baseline for negotiations among the stakeholders to find a mutually agreed strategy.

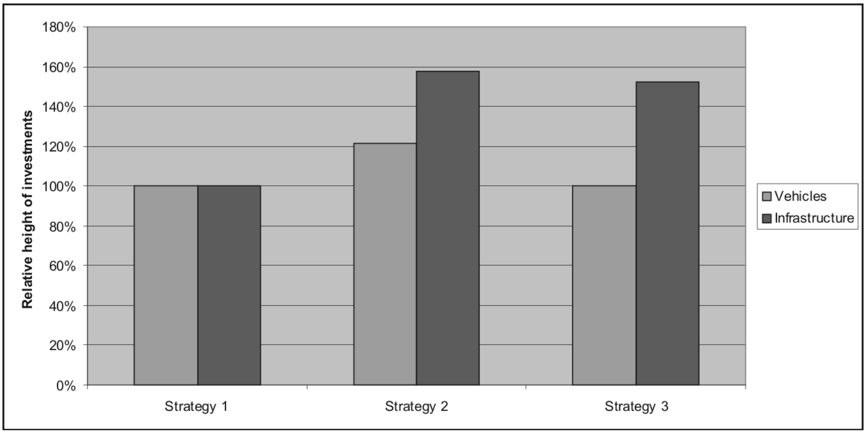

Figure 9: Compared investments of the strategies.

7 Summary

The method delivers the possibility to handle complex ATP migration problems, e.g. the introduction of ETCS on corridors. The dependencies of the equipment of vehicles and infrastructure are modelled in detail. Different scenarios of migration goals can easily be generated and compared. Each migration strategy is evaluated and optimized. Due to the detailed modelling, several performance figures can be applied for the evaluation, e.g. the net present value or life cycle costs. Furthermore, different perspectives of the optimization can be compared. Thus, the method could well be used for the negotiations along the stakeholders of the migration.

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