The influence of railway signalling characteristics on resilience

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***Abstract*—Seven disrupted scenarios have been simulated on the railway corridor Utrecht-Den Bosch, each over three signalling configurations to find the effect of in-cab signalling and reduced block section lengths on resilience. Furthermore, the place of resilience in decision making and design of railway signalling has been investigated.**

Although resilience is only one of the factors in the decision making and design of ETCS-projects, besides factors such as capacity, safety and interoperability, a quantification of resilience can help to either compare alternatives on all factors including resilience, to compare alternatives on resilience only, or to find the relation between design choices and resilience.

Simulation of seven disrupted traffic scenarios has shown that using in-cab signalling with ETCS L2 compared to line-side signalling with NS'54/ATB has saved 10% of the delay in the scenarios on average. By using reduced block sections lengths in combination with in-cab signalling, 20% of the delay has been saved on average. For absolute resilience, short block sections should be placed along the whole track. As this is not realistic from cost perspective, decreased block sections are in each case advised nearby yards and switches.

***Index Terms*—ETCS, ATB, simulation, disruptions**

I. INTRODUCTION

VARIOUS legacy protection systems in Europe have been developed mid-previous century and are due for replacement in the coming years. The European standard for railway signalling and communication, ERTMS, is the designated standard to replace these legacy systems. The signalling and control component of ERTMS is ETCS, besides components for the communication and management. ETCS is specified at four levels, in which the detection and signalling technique gradually move from the track to the train. Further explanation on the ETCS levels can be found in [1].

In the Netherlands, ETCS Level 2 is the standard level when ETCS is being implemented. At this level, train detection is still on the track-side, as with most legacy protection systems, but the movement authority is now communicated to the driver via in-cab signalling instead of line-side signals. ETCS has already been implemented on some corridors, and in the coming years, several other corridors where the NS'54/ATB is at the end of its lifetime and needs to be overhauled, ETCS will be installed.

The discussion about the planning and locations of the replacements has grown to a political and organizational debate, as a result of the amount of capital at stake and the long time span of the replacement. Now, seven corridors have been designated to be overhauled before 2030. In the decision making of implementing ETCS, several factors have been of relevance, such as the need for replacement on a corridor, the cost of the replacement, the capacity and safety benefits, and international interoperability. On the more practical side, during the design and engineering phase of an ETCS-corridor, most of the same factors are of importance on how to convert from the legacy system to ETCS. For example, a larger budget can lead to a design where the block sections lengths can be adapted, creating more capacity and resilience.

Resilience is another factor which is potentially relevant in the decision making. Resilience is the ability of a system to recover from a disruption given a predetermined control management plan.

Both in the decision making process as in the design process of ETCS, resilience is of importance: firstly on high level decision making, of where and when to convert from the legacy system to ETCS. If it is demonstrated that the latter has a large positive impact on resilience, this is in favor of converting to ETCS sooner or on more corridors. Secondly, on the level of designing the lay-out of the signalling and infrastructure. Namely, in the design of the signalling lay-out, different objectives can lead to friction between the operators and the infrastructure managers. An infrastructure manager wants less infrastructure to reduce maintenance and the amount of disruptions, meanwhile operators would like more infrastructure for their operations. A design focused on resilience can save delay for passengers during disruptions, thus saving money, and increasing passenger satisfaction.

To allow comparison of alternative designs on this factor, resilience needs to be quantified. If a method can be provided to evaluate both the cost and the benefits of a more resilient infrastructure/signalling in monetary terms, then resilience can be weighed against the other factors involved, such as cost.

This has led to the following main research question:

What is the influence of railway signalling system characteristics on resilience?

This questions is subject to several sub-questions, to split the main question in multiple components:

- *How does resilience influence the implementation and design of ERTMS in the Netherlands?*
- *Which signalling system characteristics have effect on resilience?*
- *What difference in resilience does ETCS level 2 have compared to NS'54/ATB-EG?*

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II. METHODOLOGY

To answer the research questions, several distinctive methods have been applied.

Firstly, a literature review has been used to identify the proper performance indicators for resilience, to find the relevant signalling characteristics with respect to resilience, to see the role of simulation in decision making, and to find common disruptions and disruption management strategies in the Netherlands. Secondly, interviews and expert knowledge have been used to find the role of resilience in the Dutch ETCS-decision making and designing process, to create a power-interest diagram with respect to resilience, and (iii) to discuss the set-up of simulation, the disrupted scenarios and the applied dispatching strategies.

And lastly, simulation has been used to find the impact of signalling characteristics on resilience. The corridor Utrecht - Den Bosch and the related traffic have been modelled using microscopic, deterministic simulation. Microscopic, as this provides accurate modelling of the signalling and interlocking, and deterministic, so that all other factors, such as rolling stock, timetable and running times can be controlled for. A suitable tool for this purpose is the simulation tool Xandra, developed within Arcadis. This tool has been used for the simulation of the case studies.

Seven distinctive disrupted scenarios have been set up such that they vary in duration, location and severeness, to get a representative outcome. Typical disruptions in the Netherlands and more specific to this corridor, have been distinguished via historic data on disruptions. These scenarios are then modelled over three signalling configurations to find the difference in resilience between these configurations, and hence the influence of the signalling characteristics.

Besides the typical disruptions, four types of data are needed to set up the simulation: (i) infrastructure data, (ii) interlocking data, (iii) rolling stock characteristics and (iv) scheduled operation data.

The outcome of the simulation, the delay of trains, has been processed using the computing environment MATLAB.

This approach is the most valid to find the impact of signalling characteristics on resilience since other methods are not able or suitable to capture this effect. A mathematical approach does not suffice since the effects happening in a disrupted situation that are hard to capture mathematically, opposed to that of an undisturbed operation. Comparison of historic delays at ETCS corridors and legacy system corridors would require an extensive amount of disruptions to find the pure effect of the signalling system.

III. LITERATURE REVIEW

A. Resilience

Several definitions of resilience are being used in different sectors. They all have one factor in common: the mitigation of the impact and the focus to return to the original state In the railway sector, this mitigation is specified as rescheduling actions [2] & [3]. Resilience is for this researched defined as *the ability of a system or timetable to recover from a disruption given a predetermined control management plan.*

B. Prior work

One of the studies that this research builds upon is the one from Goverde, et al. (2013) [1], who made a capacity assessment of a Dutch corridor of different signalling configurations under both normal and disturbed railway conditions. Their results showed that in delayed operations, there is a considerable gain for ETCS compared to NS'54/ATB, since the braking distances decrease when delayed trains run at lower speeds, having a stabilizing effect on headway times, delay propagation and throughput. This research will focus on larger disruptions, instead the smaller disturbed situations in [1]. It is shown how shortening the block sections can reduce the headway and the energy consumption on that line, but that it comes at extra costs [4]. It shows the force field of interests when designing a signalling lay-out. In an analysis of technical railway characteristics, it was found that the influence of block section lengths is higher for homogeneous train traffic and lower for heterogeneous traffic [5]. Furthermore, they found that reduced sections lengths around stations become more useful when the number of trains with stops at these stations is increased.

C. Performance indicators

Several performance measures have been suggest for resilience [6]: punctuality, average or maximum secondary delay, as well as average track occupation. Another three measures of resilience have been suggested, captured in a deviation area diagram. A deviation area diagram graphically shows three performance indicators: (i) the maximum deviation during a time period, meaning the maximum of the sum of the delays per moment in time, (ii) the time to recover to an acceptable threshold and (iii) the deviation area, or the sum of the delay of all trains [7].

On top of the found performance indicators, this research introduces a new indicator for resilience, the Resilience Index (RI), which is the ratio between the total train delay of a given signalling system over all scenarios, and the delay of a benchmark signalling system, multiplied by the number of scenarios.

$$ResilienceIndex = \frac{N}{\sum_{n=1}^{N}\left[\frac{\sum_{t=1}^{T} \textit{Final Delay}_{t,SignSys}}{\sum_{t=1}^{T} \textit{Final Delay}_{t,RefSys}}\right]}$$

where *N* is the number of scenarios, *T* is the number of trains, *Final delay* is the delay of a train at its final destination, and *SignSys* is the given signalling system which is compared to the reference signalling system, *RefSys*. The resilience index of the reference configuration is set to 1 by multiplying the ratio of the delays by the number of scenarios. An index larger than 1 indicates a more resilient signalling configuration, and an index smaller than 1 a less resilient configuration.

Taking the reciprocal of the resilience index gives the average percentage of delay a configuration can save compared to the base configuration. This delay saving can be used to translate the benefit of a configuration for an economic evaluation and identify the corresponding monetary savings.

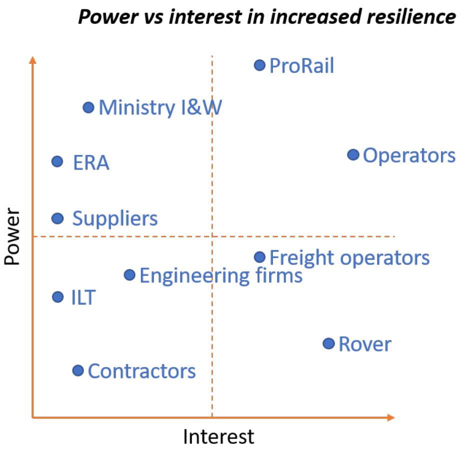

Fig. 1. The power vs interest of stakeholders in increased resilience

D. ETCS implementation and design process

A stakeholder based approach has been used to see which stakeholders have most interest in an improved robustness of the train traffic and what their respective power is in the decision making process. It can then be seen which stakeholders benefit most from increased resilience.
The Dutch ERTMS program has divided the 190 stakeholder organizations into several groups: Operators, governments, companies in the harbour, passenger organizations (e.g. Rover), infrastructure managers (ProRail), European instances, market parties, such as contractors, suppliers, and engineering firms, and inspectors (e.g. ILT).

Each of these groups have been placed in a power/interest-diagram, with help of an interview and expert knowledge [8], shown in Figure 1. It shows how much power a group has in the decision making process versus its interest in increased robustness of the train traffic.

Research into resilience may be of most importance to NS, ProRail and engineering firms, and not so much to the ministry, as their focus is more on safety and replacing old infrastructure than on robustness. For NS and ProRail, however, it will be interesting to find out the effect of ETCS on the resilience of their timetable and their contingency plans. For engineering firms, quantification of resilience may be of influence to how they will design future signalling lay-outs.

A method to show the relation between resilience and signalling characteristics can help designers and decision makers on several levels, based on the need and the available information. Three levels can be distinguished:

1) Full comparison: fully developed method in which alternatives can be compared between themselves as well as with other factors. The benefits and costs can be expressed such that non-experts are able to include resilience in the decision-making.
2) Comparison between alternatives: results are complex to translate to monetary terms in the method and can therefore only be compared among themselves but not with other factors.

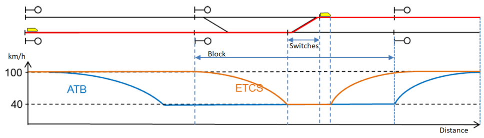

Fig. 2. Comparison of braking curve between ATB and ETCS

3) Expert judgement needed: the method is to be used as a tool to find the relation between alternatives. The results are not convertible to monetary terms and decisions have to be based on expert judgement of the results.

E. Signalling characteristics

A railway safety system can normally be divided into four sub-components [1]:

(i) *Automatic train protection*, which supervises the speed and braking curves of a train. The communication and supervision can be intermittent or continuous, or a combination. Continuous systems have shown to reduces ATP capacity penalties and to improve headway. Another disadvantage to intermittent systems is that a train is being restricted to the braking curve imposed by a distant signal. The way the braking curves is supervised, varies per signalling systems. In NS'54/ATB, the driver has to start braking right at the signal with the 'yellow' aspect and continue at 40 km/h up to the red signal. In ETCS, however, the train calculate its braking curve up to the end of the movement authority and is thus able to postpone the braking until necessary.

(ii) *Movement authority communication*: Related to the ATP is whether the movement authority is communicated to the driver via line-side signals or via in-cab signalling. Driving with optical signals implies that the location where to start braking is fixed for all trains, while the initial speed is adapted in order to match the braking performance of the train, or in other words, poor braking trains must drive slower to still have the same block length [9]. From the point of train separation, the essential benefit of a system with cab signalling compared with a system with line-side signalling is the independence of the cab signals from the approach distance of the line-side signal system, which allows trains to run a higher speeds locally [10].

(iii) *Train detection*: On the track-side there are two main methods to detect the presence of a train in a section and separate trains, namely via track circuits and axle counters. Track circuits are based on a electrical circuit using the rails, to detect the presence of a train in a section. Axle counters detect train traffic by counting train axles crossing the border of a section using a counting head. The main advantages of axle counters over track circuits are that the length of the sections are virtually unlimited, that no insulating joints between sections are needed, and generally less installation and maintenance costs. Which system has been implemented is mostly a historical precedent. It is also possible to separate train safely using only train-based systems, as in ETCS L3. In this signalling system, the train itself send its position, length and integrity status to the interlocking system to release (digital) track sections [11]. This thus requires an extra train integrity monitoring (TIM) system.

(iv) *Interlocking* is a system composed by a set of signal apparatus that prevents trains from conflicting movements through only allowing trains to receive authority to proceed, when routes have been set, locked and detected in safe combinations. Its main function is to set and lock routes related to each train located in an area under its responsibility, in order to ensure safe movements along the track.

Various subsystems of railway signalling have been identified, but only two relevant signalling characteristics for resilience: the length and number of the block sections and in-cab signalling vs line-side signalling. Reduced block section lengths allow for smaller headways, especially in disrupted situations, when train are following one another closely at reduced speeds, this is of importance. In-cab signalling is important as this allows for more optimized braking curves, thus trains maintain higher speeds for a longer time and can follow one another better through speed restricted situations.

F. Typical disruptions and dispatching

The purpose of a resilient system is to overcome disruptions. This section will therefore discuss which typical disruptions normally have to be overcome on a railway, and especially on the Dutch network.

A disruption can have a plethora of reasons. Eight sources of disruptions have been differentiated that take place at the Chinese high-speed rail network, a categorization which is likely to be also valid for other railways [12]:

- Bad weather: snow, rain, fog, etc.
- Vehicle on-board equipment failure: smoking alarm, failure of train control system, etc.
- Train body failure: bogie or wheelset failure, etc.
- Communication equipment failure: GSM-R failure, transponder failure, etc.
- Track system failure: switch or rail failure, etc.
- Electric related failure: pantograph breakdown, overhead wire failure, etc.
- Dispatching human interface failure or alarm
- Other: e.g. collisions

The severeness and impact of disruptions and the needed disruption management can be classified in two categories according to [13]: partial blockage and full blockage. In the first case, partial train traffic is possible, but balancing of the trains is needed. Examples of this are that from two tracks only one can be used, or that the the speed is restricted. In the full blockade case, no traffic at all is possible across a certain point in the line.

The following sources of disruptions have been identified as disruption where different signalling systems are likely to give a different outcome, and are thus interesting to be investigated: (i) collision, (ii) level crossing failure, (iii) signal failure, (iv) faulty train, and (v) switch failure.

The EU ON-TIME project states that resilience requires knowledge of the traffic control measures. The most common dispatching measures are therefore described here:

For the real-time rescheduling of the railway traffic during disruptions, by dispatchers as well as rescheduling tools, three main actions can be taken [14]: retiming, reordering and rerouting. In case of a full blockage, some extra actions or decisions are possible for the dispatcher, namely short-turning of services, cancelling services, extra stopping and stop skipping. This is done to isolate the impact of the disruption to adjacent areas.

IV. CASE STUDY

The Dutch railway corridor Utrecht - Den Bosch was chosen for the simulation, since the number of trains on this corridor is sufficiently large, the headways and buffers between trains are small, physical traffic rescheduling measures are possible, and the train traffic is heterogeneously enough to provide interesting results.

The corridor is approximately 50 kilometers long, starting and ending at the main stations of Utrecht CS and Den Bosch, where the intercity trains stop, and with seven intermediate sprinter stations. Four of the sprinter stations (Vaartsche Rijn, Lunetten, Houten and Houten Castellum) are along the four track section, separated from the intercity trains. Culemborg and Zaltbommel are placed at the double track section, and Geldermalsen is a larger hub for sprinters, where overtaking is possible. Traffic on this route consists per direction of three half-hourly non-stop intercity services between Utrecht and Den Bosch, two half-hourly sprinter services between Utrecht and Geldermalsen, one of which continues to Den Bosch, and an hourly freight train from Utrecht to the branch to the Betuweroute.

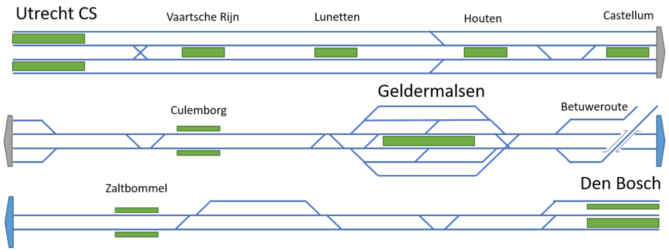

Fig. 3. Infrastructure layout as used in this research

The intercity services are all driven with VIRM train sets, the sprinters by SLT train sets, and the freight trains are commonly two BR189-locomotives pulling a coal train.

A. Disrupted case scenarios

Based on the typical railway disruptions from the literature and historic data on disruptions on the corridor Utrecht - Den Bosch, seven disrupted case scenarios have been set up.

1) *ATP defect*: Due to damage to the ATP signal receiver, or loss of communication with ETCS, a service has been restricted to 40 km/h until a location where it can be taken out of service;
2) *Train engine defect*: Due to a mechanical failure, a service has stranded along the open tracks and needs to be towed away by another service or tow locomotive;

3) *Switch power failure*: the control of a switch can be lost due to a cable/power failure. It can be clammed in one direction so that traffic can pass in that direction anyhow
4) *Damaged switch rod*: when a switch rod has been damaged, no traffic is allowed over said switch until it has been repaired, and is thus redirected as much as possible via other tracks;
5) *Level crossing failure*: several reasons can lead to a failure of a level crossing, which then closes automatically. All services have to cross it at 15km/h to ensure no one is passing the level crossing;
6) *Incorrect track occupation*: A failing track circuit leads to an incorrect track occupation, meaning all drivers have to get explicit permission from the dispatcher to pass that section at reduced speed;
7) *Collision with a vehicle*: after a collision, the tracks are blocked until emergency services have cleared the tracks.

B. Signalling configurations

In the literature review, two signalling characteristics have been distinguished which are most likely to be relevant for railway resilience, namely the block section lengths and whether the movement authority is provided via in-cab signalling or via line-side signals. To test the effect of both the characteristics separately as well as the combined effect, three signalling configurations will be modelled.

Firstly, the current NS'54/ATB-EG signalling configuration, as constructed outside, will be modelled. Data about the location of stations, switches, (relation between) signals, and speed limit markers is imported via the drawings made by Arcadis of the infrastructure layout.
Secondly, an ETCS Level 2 copy of the ATB configuration will be modelled. This configuration uses the existing blocks for track detection and the same placement of 'signals', which are now just marker signs. Lastly, an ETCS Level 2 with reduced block sections will be modelled. The blocks sections lengths are reduced to 200 meter, to approximate the effect of the moving block principle.

By comparing the second configuration to the first one, the potential effect of in-cab signalling over line-side signalling is tested, thus ETCS L2 over NS'54/ATB, whilst controlling for the block section lengths. Comparing the third configuration to the second configuration, gives the potential effect of short block section lengths over the current block section lengths in ETCS L2. The combined effect of both characteristics can be observed when comparing the third configuration to the first one.

To validate the train behaviour in the model, a comparison is shown in Figure 4 and 5 of a modelled train having to brake several times, either to stop or to enter a speed restricted situation. From here, it can be seen that the ETCS L2-train brakes later, in space as well as in time, and that is not effected by the 'yellow'-aspect, which can be seen for the ATB-train near km 18. Only one ETCS L2 configuration is added in Figure 5, since the blocking distance is not of influence to the the braking behaviour with ETCS L2 in such situations.

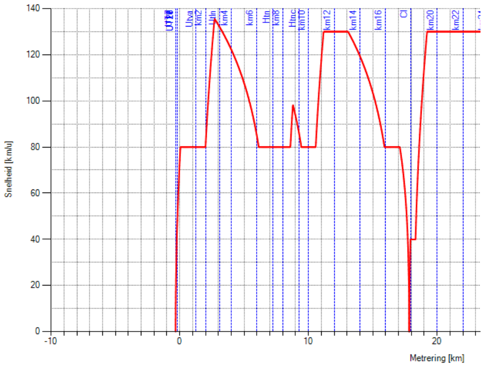

Fig. 4. Driving behaviour with NS'54/ATB

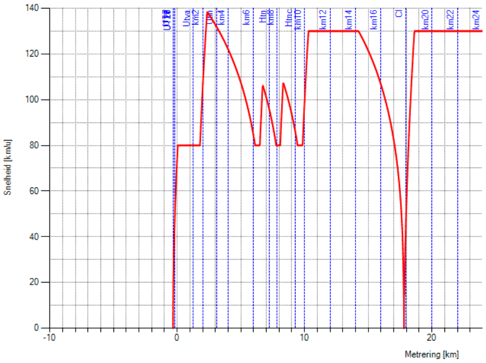

Fig. 5. Driving behaviour with ETCS L2

V. RESULTS

Tables I and II show the outcome of the simulated scenarios on two performance indicators: (I) the time until the total delay in the system has decreased below five minutes, and (II) the total delay of trains at their final destination, compared to the base configuration NS'54/ATB.

TABLE I
OVERVIEW OF HOW QUICKLY THE DISRUPTION HAS RESOLVED IN EACH CONFIGURATION PER SCENARIO (H:MM)

Scenario	NS'54/ATB	L2 existing	L2 reduced
1	0:55	0:45	0:43
2	0:46	0:40	0:30
3	1:06	1:06	1:06
4	1:05	1:03	1:01
5	0:49	0:49	0:43
6	0:51	0:51	0:51
7	1:13	0:59	0:45

TABLE II
OVERVIEW OF THE DELAY PER CONFIGURATION PER SCENARIO COMPARED TO THE ATB CONFIGURATION

Scenario	NS'54/ATB	L2 existing	L2 reduced
1	100%	-9.1%	-12.9%
2	100%	-13.6%	-25.1%
3	100%	-19.2%	-19.3%
4	100%	-9.0%	-12.6%
5	100%	-2,2%	-27.9%
6	100%	-3.0%	-11.5%
7	100%	-11.8%	-28.6%

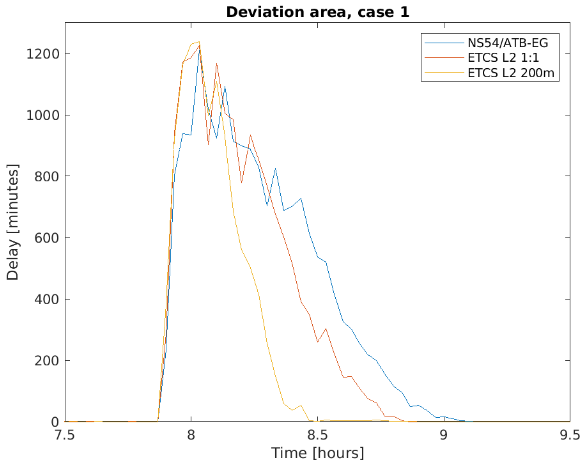

Fig. 6. Deviation area diagram of the 7^{th} scenario

Figure 6 shows the deviation area diagram of the 7^{th} scenario. Here, it is visible how the delay decreases quicker in the ETCS configurations than in the ATB configuration. The peak of the ETCS configuration are earlier in time and larger because the train services are restarted quicker, meaning that trains pass delay measuring points earlier in time.

The outcomes of the total delays of the scenarios are in a wide range, from -2,2% to -19% for the L2 existing blocks and from -12% to -28% for the reduced blocks. This is logical as the scenarios vary in length and severeness. In spite of the large differences in outcome, they do indicate that significant reductions of delay can be achieved by firstly upgrading to ETCS Level 2, and secondly by reducing the block sections for train detection. This is in accordance to the hypothesis in the theory that both of the signalling characteristics would increase the resilience.

The resilience index of the ETCS configurations can be calculated according to formula in the literature review. . For the ETCS L2 with existing blocks configuration, the resilience index compared to the base ATB-configuration is 1.10. For the L2 reduced blocks configuration, the resilience index is 1.25. This means that with the L2 existing configuration 9% of the delay has been saved in the modelled scenarios on average, and the L2 reduced one has saved 20% of the delay over all scenarios.

In the 1^{st}, 3^{rd} and 4^{th} scenario, most of the benefits can be achieved by implementing in-cab signalling. Only a small extra benefit is obtained by reduced block sections length. In the other four scenarios, the reduced block section lengths were able to reduce the delay more than the in-cab signalling.

The simulation show that especially in short speed-restricted disruptions, such as switching over between tracks back and forth, the in-cab signalling part of ETCS L2 can make a difference. So, the more heterogeneous the train traffic, the more the traffic would have to brake in disrupted situations, and the more the traffic would profit from ETCS L2. Also, the short block sections show to be of great importance around switches and station areas, which are situations where traffic merges and splits or where the headways between trains become small.

In-cab signalling in combination with small blocks has lead to a significant increase of resilience in these scenarios. This strengthens the case of adjusting the current blocking lay-out to smaller blocks, when converting to ETCS, increasing the capacity as well as the resilience.

A. *Discussion*

The results of this study are only applicable to corridors that have a similar intensity of the traffic. On corridors with less traffic and/or larger headways between trains the potential benefits will be smaller. For an even better comparison of the signalling characteristics, an extra configuration could have been simulated, namely the NS'54/ATB system with the smallest blocks as possible in that system. No differentiation has been made between the configurations to the used dispatching measures, to test the pure effect of the signalling characteristics and not that of the dispatching. For this, a larger network should be taken into account, as the dispatching measures are also of larger influence than just one corridor. Moreover, the results are dependent on the time and location of the disruption, the length of the trains, which trains has been chosen to be disrupted, the timetable on the corridor. Different input would have potentially led to a different outcome. The simulation tool Xandra assumes trains drive at full power and speed, a driving behaviour which is not applied by drivers in reality.

VI. CONCLUSION

A. *Key findings*

The following conclusions have resulted from the literature review, interviews and simulations:

- The resilience of the signalling system is just one of the many aspects to be considered in the infrastructural decision process of ERTMS. More important criteria are safety, the need for replacement, interoperability and cost;
- Increased resilience is most interesting for operators and passenger organizations; the power, on the other hand, lies in the hands of ProRail and engineering firms, as they are the ones responsible for the design of the lay-out of the signalling and infrastructure;
- There are three levels in the design phase of ETCS where resilience can be of support: full comparison between alternatives on all factors, including resilience; comparison between alternatives, but only on resilience; and to find the relation between design choices and resilience, based on expert judgement of the results of a resilience study;
- Two signalling characteristics are of relevance for resilience: the placement and length of block sections and whether the movement authority of a train is provided to the driver via line-side signals or via in-cab signalling;
- The modelled disruption scenarios has shown that compared to the current Dutch NS'54/ATB signalling configuration, an ETCS L2 configuration that uses the same block distances is 10% more resilient; An ETCS L2 configuration with reduced block section lengths of 200 meters is up to 25% more resilient than the current

NS'54/ATB signalling configuration. The effect of reducing the block sections lengths in ETCS L2 to an approximation of the moving-block principle is thus 13%;
- With very short block section lengths, the potential benefits is restricted by factors other than the signalling component, such as platform capacity or the speed difference between trains.

B. Recommendations

Up to 10 or even 20% of passengers delay can be saved by installing ETCS L2, and by reducing the block sections lengths. This means that installing ETCS L2 not only increases the safety and capacity, but also helps to reduce the effect of disruptions, thus cutting down the costs for operators and increasing passenger satisfaction.

The benefits of increased resilience needs to be weighed against the costs of increasing the number of block sections. Designers can either use the results of this research or an appliance of this method to the concerned design area to underpin their design choices. The method used is also useful to assess the benefits of spatial dispatching possibilities, such as side-tracks and switches. The delay saved for passengers and freight, due to the increased resilience, then can be weighed off against costs and other criteria.

In the design phase of any future ETCS L2 lay-out, a trade-off should be included between the costs for extra infrastructure or signalling components, which increase the resilience and decrease the cost of disruptions. It can be decided to use the existing block sections or to use smaller block sections lengths, which costs extra but also increases the resilience. Furthermore, this simulation approach can be used to optimize the block sections lengths, and find which block sections are unnecessary regarding resilience. Operators can use these findings to calculate the estimated reduction of cost when having shorter disruptions, and strengthen their negotiation point to have a more resilient infrastructure. Although it is not required to take it into account since many other factors are of importance too, it can help the decision making or designing process.

C. Further research

In this research, only simple traffic management has been applied, and even the same strategy in the ATB and ETCS L2 configurations to give a fair comparison. Research can or must be done on how traffic management will change when ETCS L2 will be implemented on more parts of the Dutch network. For this, a larger network should be simulated than this one corridor, as then more distinctive dispatching possibilities can be simulated.

It was beyond the scope of this research to find an optimal blocking lay-out strategy for the ETCS L2 configuration. However, this is interesting for further research to help the design of future ETCS L2 routes. It could be done with the simulation approach used in this research. In the ETCS L2 reduced blocks configuration, per case one could remove the blocks that have no influence on the outcome of the simulation of that case. Doing this for several cases may give an optimal blocking configuration strategy with respect to resilience.

This simulation approach could also be used to find which spatial dispatching possibilities, such as switches and side tracks, are relevant for the resilience of the train traffic and which are not and thus may be removed.

Further research is also recommended on the effect of combining ETCS with Automatic Train Operation. Research may be done to see what blocking distance strategy is most optimal for ATO over ETCS, what the expected capacity and robustness increase is with ATO, how the standards for headways between trains can change, how traffic management can or should change, and how the (specification and requirements for) the on-board and track-side systems are affected.

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