TRIZ Super-Effect Analysis and Secondary Conflict formulation as part of a structured technology development learning cycle.

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Abstract. For many years the rail industries in temperate countries have struggled to deal with the effects of low adhesion between the train wheels and track due to leaf fall in the autumn – the so-called problem of "leaves on the line". During autumn, it is common in the UK for this problem to lead to journey delays and service cancellations. Annually, low adhesion mitigation costs the UK rail industry over £50 million. This paper builds on work originally presented at TRIZ Future 2016 and describes the development of one proposed solution to low adhesion. A typical structured technology development learning cycle is presented and used to highlight key stages in the growth of the concept. The solution is used as a case study to show how Secondary Conflict formulation and Super-Effect Analysis were applied; delivering a more robust final product and exposing further opportunities for rail industry innovation.

Keywords: TRIZ, Low Adhesion, Rail Industry, Learning Cycle, Secondary Conflicts, Super-Effect Analysis.

1 Background to the low adhesion problem

Low adhesion is a long standing and costly problem for the UK rail industry. When a train driver applies the brakes of a train approaching a signal or station, the greatly reduced rate of train deceleration under certain rail conditions can lead to an increased occurrence of safety related incidents, requiring many expensive mitigation measures to be used. The problem is compounded as the braking performance of the train in low adhesion conditions is often very difficult to predict. Low adhesion occurs most frequently in autumn and spring and is thought to be the result of external contamination (for example tree leaves) between the rail and wheel. As train drivers cannot be sure where low adhesion might occur they tend to adopt a more conservative braking strategy when they believe there is a higher risk, resulting in increased and unpredictable journey times between stops. Even though the UK rail industry issues a special autumn timetable with longer allowed journey times, low adhesion is often cited as the cause of service train delays. Low adhesion is set to become an even more critical issue in future, with the planned introduction of ERTMS (the European Rail Traffic Management System) and possible fully-automated train operation (e.g. driver-less trains). For example, ERTMS must make an assumption of expected braking rates; if these have to be made more conservative to allow for the effects of low adhesion, the distance between all trains must increase and the capacity of the rail network is greatly reduced.

2 The methods used to develop a low adhesion solution

Following a UK rail industry commissioned TRIZ-based study into low adhesion, several solution directions were proposed [1]. Rail industry funding was provided to support the demonstration of a selection of these solutions. This paper outlines the development of one such concept option and describes how a key secondary conflict for this concept was addressed. TRIZ Super-Effect Analysis is also used to explore and expand the potential of the resulting concepts.

2.1 The proposed solution

The proposed solution uses a train-mounted controllable water delivery system to increase the amount of water present at the wheel rail interface of the train during low adhesion events. Water plays a critical role in the creation and removal of the low friction rail coating. Many rail industry studies have shown that wheel-rail friction reduces greatly when a small amount of water is present [2, 3, 4, 5]. If water can be added to the wheel rail contact point when low adhesion is detected it should improve the level of friction available to slow the train.

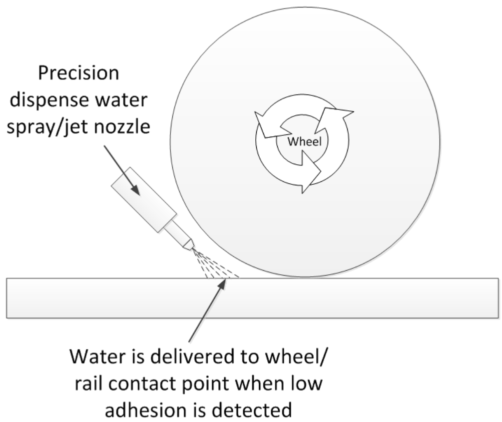

Fig. 1. Train-mounted water delivery system concept.

The delivery of water to the rail is also likely to have a positive impact on the contaminant layer itself, softening and accelerating the removal of the coating from the rail. Figure 1 shows a concept diagram of the train-mounted water delivery system.

2.2 Technology development learning cycle

Laboratory research into the water addition concept was initiated in 2015 and a full-scale train-based test programme has been underway since January 2018. A number of secondary issues have been highlighted and addressed during the development of the water delivery system. In general, these problems have been dealt with through iterative concept prototyping and testing, using the typical learning cycle shown in figure 2.

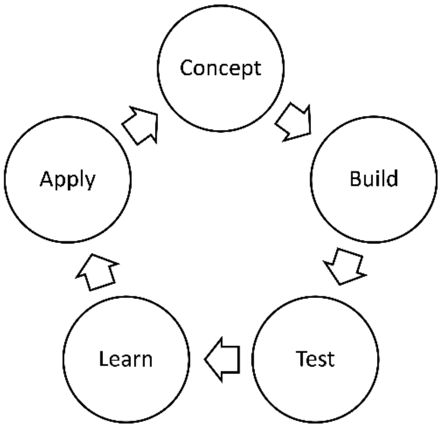

Fig. 2. Technology development learning cycle.

The technology development learning cycle has close parallels with the iterative, time-bounded series of activities recommended in the “Agile” methodology [6] which is often described as a “Sprint”.

This paper charts the progress of one key issue through this cycle and shows how it was analysed and addressed using TRIZ Secondary Conflict resolution and subsequent Super-Effect Analysis. The following section provides further detail on the activities undertaken within each part of the cycle.

Concept The objective of the learning cycle is defined. The solution is proposed and a prototype design prepared. The test plan and supporting equipment is detailed.

Build The solution is embodied to enable testing to be performed. The solution may be in the form of a software model or physical hardware.

Test The solution is tested against the test plan. Test results are analysed and prepared for review.

Learn The test results are reviewed. Key learning points are listed. Where necessary, underlying physical principles are understood and recorded. System limitations and conflicts (including any secondary conflicts related to the new technology) are formulated.

Apply TRIZ methods are used to resolve the conflicts and limitations identified in the previous step. Basic conceptual solutions are developed and screened. Improved solutions are proposed, enabling further learning cycles to take place. TRIZ Super-Effect Analysis is applied to the chosen solutions, potentially enabling other conceptual solutions (with their own associated learning cycles) to be defined.

2.3 Secondary Conflicts

TRIZ provides tools to enable problems to be defined (in the form of a System Conflict) and resolved. TRIZ is based on the study of successful innovations from a wide range of industries, which means that problems are often solved by importing a well-proven technology solution from one industry into another. When a solution arrives in an alien problem environment it is common for secondary issues to arise. In conventional problem solving, Secondary Conflicts can present insurmountable barriers to the implementation of promising technologies and concepts. TRIZ, in contrast, encourages the user to expect Secondary Conflicts and required that they are deliberately exposed at an early stage. The resulting conflict statements are treated as starting points to create a differentiated and robust solution to the problem.

2.4 TRIZ Super-Effect Analysis

New solutions introduce additional resources into a system or, at least, rearrange those already present. When Altshuller originally developed ARIZ, he included steps to encourage users to reflect on the process followed during the problem analysis and to seek out other solutions that the new system might provide. Some concepts realised through this form of review can provide greater benefits than the original idea. Sadly it is uncommon, even amongst TRIZ practitioners, for new ideas to be evaluated in this way. Super-Effect Analysis provides a structure to enable innovators to explore the potential of their solutions [7]. The algorithm for Super-Effect Analysis is detailed as follows:

1. Describe the improved system. It may be necessary at this stage to imagine the new conceptual solution in the context of the initial (existing) system.
2. List all the changes to the initial system.
3. Identify all the new features and properties of the improved system.
4. Using the new features and properties as a resource, improve the system. Consider applying the new resources to analogous and related systems – i.e. through Feature Transfer [8].

5. Describe the next generation of the improved system. If necessary, review and adjust the physical properties of the improved system to match the new situation.
6. Repeat steps 1-5 as desired.

3 Applying the methods to address a key secondary conflict for the water addition concept

Available storage space on service trains is often at a premium. This imposes a constraint on the volume of water which can be stored and supplied to the rails from a train-mounted water delivery system. Initial tests indicate that a relatively small amount of water added to a low adhesion rail can still provide a significant recovery in braking friction, but the resulting low delivery rate of the water means that the system has increased susceptibility to aerodynamic effects. Higher train speeds and strong cross-winds may deflect a low pressure water jet away from the rail surface and lead to greatly reduced levels of water delivery to the rail. In fact, the issue of poorly controlled delivery is well recognized in the rail industry – the dispensing of liquid friction modifiers such as traction gels to the wheel rail interface can often be adversely affected by cross-winds and turbulence. The existing solution to this problem makes use of a flexible boot to exclude aerodynamic disturbance. Figure 3 is a partial functional process model for the water addition concept which shows the key secondary conflicts faced by the water addition concept in the context of the rail application. Useful actions are shown as plain text, insufficient actions by fine dashed arrows and harmful actions using bold, underlined text.

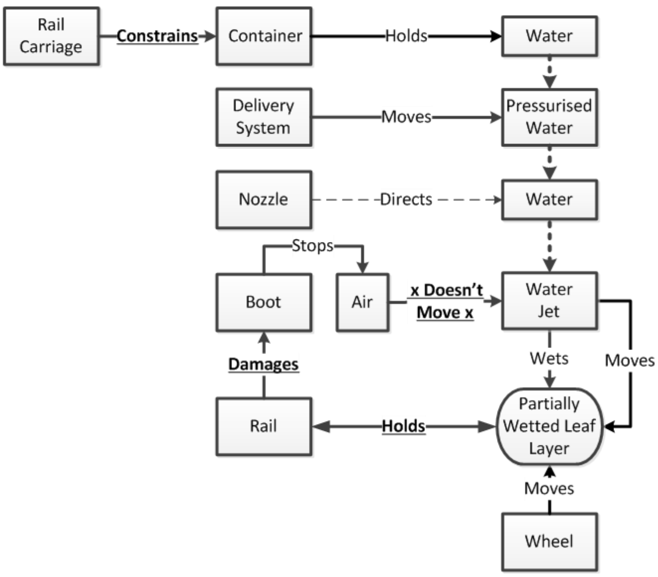

Fig. 3. Key secondary conflicts faced by water addition system.

The next section reviews one of the key system conflicts for the water addition concept in greater detail.

3.1 The Secondary Conflict for friction modifier guidance

Existing rail industry solutions such as protective flexible boots and rubber hose ends have evident limitations in the unforgiving rail environment, being easily damaged or displaced. This situation can be expressed for a generic "friction modifier" as the conflict shown in figure 4.

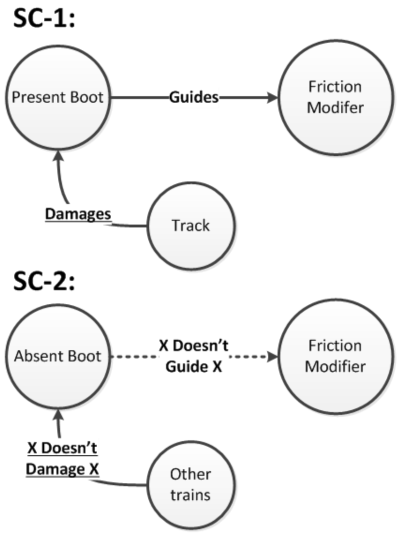

Fig. 4. System Conflict for friction modifier delivery.

Taking the boot as the key component of interest, the system conflict is converted into a physical contradiction which can be stated in the following way [9]:

PC-1: To provide the useful action "guides friction modifier", the boot should be present.
PC-2: To eliminate the harmful action "track damages boot" the boot should be absent.

3.2 Resolving the Secondary Conflict for friction modifier guidance

A technological system usually performs one or more primary functions, supported by one or more auxiliary functions. Primary functions are delivered by system components known as main tools and auxiliary functions by auxiliary tools. Auxiliary tools can be further classified (in descending order of importance) as enabling, enhancing, measuring and correcting [10]. When the functions of the components of this system are analysed, it becomes clear that the boot is performing a corrective auxiliary function and as such, should be eliminated [11]. This leads to the following statement of the Ideal Final Result (see figure 5) in which the x-component is preferably an existing, readily available system resource.

IFR
We need to introduce an X-component which guides the friction modifier to the rail without being damaged by the track

Fig. 5. Ideal Final Result (IFR) for absent boot.

Resources available at or near the conflict domain include air, the train wheels, the train's mechanical and electrical systems and the rails themselves. These resources provide the basis for multiple solution options. For the purpose of this paper only one option will be studied: use of electrostatic attraction to guide the friction modifier (in this case water) to the rail. Figure 6 shows a concept which uses an electrostatic potential to deliver water from an outlet nozzle to the rail. The electrostatic field at the nozzle induces a "mirror" charge in the earthed conductive surface (the rail) and the potential difference formed attracts the charged droplets from the nozzle and towards the earthed surface. This represents the *Concept* stage of the learning cycle described in section 2.2.

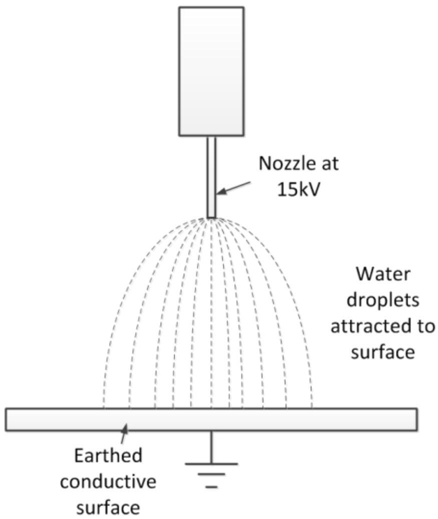

Fig. 6. Electrostatic water delivery concept.

This concept was built and tested (the *Build* and *Test* stages of the learning cycle) but the results of the tests were disappointing to say the least! Rather than increasing water delivery to the earthed surface, the amount of water delivered reduced significantly when the electrostatic field was switched on! Why should this be? Surely the electrostatic field ought to increase water delivery by attracting water droplets to the surface. The problem was analysed during the *Learn* stage of the learning cycle and the charge on the droplets was found to be in conflict – see figure 7.

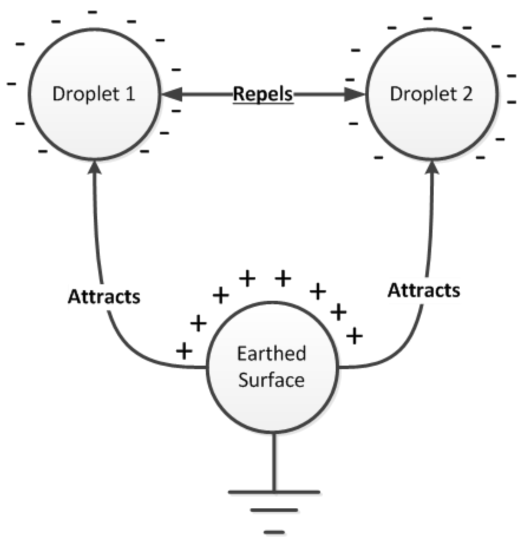

Fig. 7. Charged droplet action diagram.

The useful action of the electrostatic charges on each droplet is shown as “attracts”; the harmful action (shown as underlined text) between the two charged droplets is “repels”. The analysis showed that the opposing charges on the droplets might well result in the water delivery to the surface becoming more diffuse. This potential conflict contains a sharp physical contradiction which can be stated in the following way:

PC-1: To provide the useful action “attract droplets to the earthed surface”, the droplets should be charged.

PC-2: To eliminate the harmful action “droplet 1 repels droplet 2” the droplets should not be charged.

With the water delivery problem stated in this way, it becomes clear that the “charged/not charged” contradiction should be separated in time. At time 1 the droplets should carry no charge to avoid mutual repulsion and at time 2, the droplets should be fully charged to enable them to be attracted to the earthed surface. The TRIZ conceptual approach of “separate in time” forms the outcome of the *apply* stage of the learning cycle. In the *concept* stage, the “separate in time” principle inspires a new concept of post-charging using a separate, high voltage corona electrode to generate a stream of ionized particles to charge droplets in a jet of water, causing the water to be attracted to the earthed surface without causing the jet to become more diffuse. This concept is shown in figure 8. Subsequent prototype testing showed that the new format significantly increases water delivery to the rail, even in simulated cross-winds. The next part of this paper reviews how Super-Effect Analysis was used to explore further benefits and opportunities for this solution.

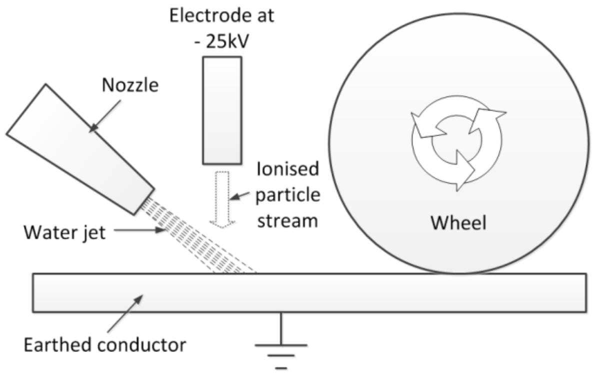

Fig. 8. Post-charging concept using a corona discharge electrode.

3.3 Super-Effect Analysis

The Super-Effect Analysis algorithm is applied to the post-charging concept as follows:

Describe the improved system.

A system comprising a high voltage source and an earthed conductor which generates an energetic ionized air particle flow between the electrode and conductor. Some of the ionized particles transfer their charge to the water droplets passing below the electrode, causing them to be drawn towards the earthed conductor.

List all the changes to the initial system.

Added electrode, corona discharge, charged water droplets.

Identify all the new features and properties of the improved system.

- Electrode – high negative direct current voltage (approximately -25kV)
- Corona discharge – negatively charged electrons which excite oxygen molecules to generate oxygen atoms and ozone. The energetic particles emerge from the ionization region where they are produced and are carried by the electrostatic potential difference to create an “electric wind” which has momentum towards the earthed conductor [12].

• Charged water droplets – carrying a negative charge and containing dissolved gasses (such as ozone) with momentum towards the earthed surface. Water is highly conductive which means that it will rapidly lose any charge when it contacts the conductor.

Using the new features and properties as a resource, improve the system. Consider applying the new resources to analogous and related systems.

The high negative DC voltage could be switched or varied to increase the level of control over water addition. This feature might be used to change the rate or direction of water delivery at different train speeds.

The energetic negatively charged electrons from corona discharge are commonly used to pre-condition surfaces to improve their wettability in industries such as coating, laminating and printing. Corona discharge treatment could be used to improve the wettability of the rail surface contaminants, improving the rate of water absorption into the contaminant layer.

The ozone generated by corona discharge in air is known to be highly oxidising. Ozone is commonly used in sanitising applications in the food industry and for cleaning surfaces of organic matter. Ozone might enhance the removal of contaminants from the rail surface. NB The presence of ozone might also increase rail corrosion – a potential negative consequence of this solution which highlights a further secondary conflict.

Other analogous and related systems in the rail industries are used to deliver friction modifiers such as traction gel and sand. Some water-based traction gels are likely to behave in a similar way to water, however, oil-based traction gels and sand have much lower conductivity values and can be expected to interact more strongly with an electrostatic field. The new electrostatic post-charge concept might provide important benefits when used with sand or oil-based traction gels.

Describe the next generation of the improved system. If necessary, review and adjust the physical properties of the improved system to match the new situation.

The Super-Effect Analysis yielded multiple options to improve train traction and adhesion related systems. The final section of this paper describes one of the more promising outcomes from this work.

4 An improved sand delivery system

In the rail industry, low adhesion has traditionally been combatted by firing sand directly into the wheel/rail contact from on-board the train. All UK rail passenger service trains are fitted with sanding systems. Sand is delivered into the wheel–rail contact via a hose from a storage hopper mounted to the under frame of the train. It has been shown that relatively small movements in the hose/nozzle (which is often poorly set up on UK rolling stock) from its ideal position and the presence of cross-winds can significantly reduce sand entrainment. In fact tests indicated that even moderate side winds may be enough to render sanding systems completely ineffective in the field [12]. As with other friction modifiers, the effective delivery of sand to the wheel-rail interface in real conditions can be highly problematic. Any solution which measurably improved sand delivery would be of significant interest to the rail industry.

4.1 The proposed concept

The proposed solution uses corona post-charging to produce a stream of ionized particles which confer a charge to the sand particles as they pass below the electrode. The electrostatic field at the electrode induces a “mirror” charge in the rail and the sand is attracted to it. Figure 9 shows the corona post-charge sand delivery concept.

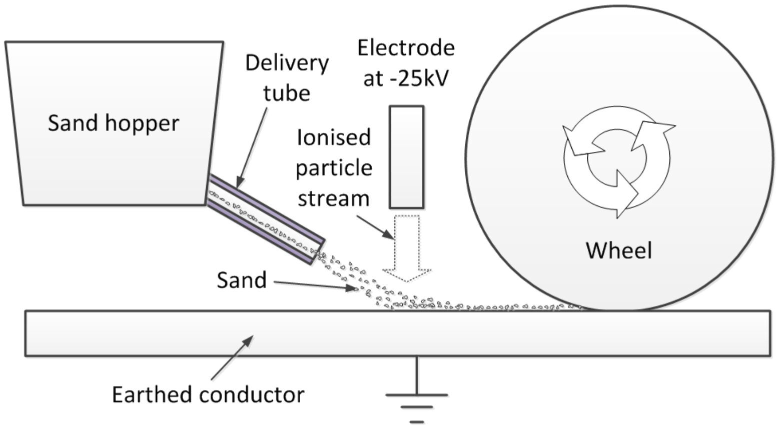

Fig. 9. Corona post-charge sand delivery concept.

4.2 Prototype test results

A basic prototype system was built to assess if an electrostatic field might improve the robustness of sand delivery. Sand was delivered by hand to an earthed metallic bar mounted at 45º to horizontal above which a corona discharge electrode was mounted. Without the electrostatic field energized, the sand flowed normally under gravity but when the electrostatic field was switched on the sand particles became trapped on the bar even before they had even reached the corona electrode – see figure 10. The magnitude of this effect was entirely unexpected and very exciting for the developers! The sand only resumed its journey under gravity when the electrostatic field was switched off. These results have subsequently been replicated in further tests and on a full-size rail system.

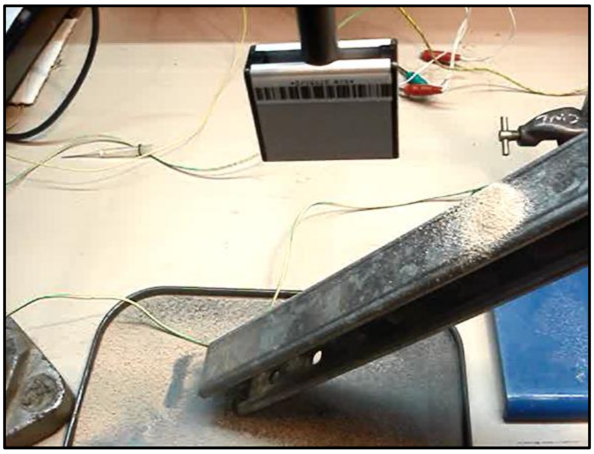

Fig. 10. Prototype testing of sand delivery concept – electrostatic assist on.

5 Conclusions

The case studies outlined in this paper highlight the importance of taking a robust and iterative approach to Secondary Conflict identification and resolution during new technology development. One might be tempted to think that TRIZ delivers solution which are so good that further refinement is unnecessary. In reality, the reverse may be true – as TRIZ often brings technologies from parallel industries into an alien problem environment, Secondary Conflicts should be regarded as inevitable for all but the most trivial solutions. The concepts presented demonstrate the power of Super-Effect Analysis – a series of simple questions and tools to encourage innovators to get the most from their solutions. The resulting solutions are now the subject of feasibility studies with further rail industry research proposals being prepared. So far, the work described in this paper has directly led to the filing of one UK patent application in March 2018. As further iterations continue it is likely that more innovations and IP will result.

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