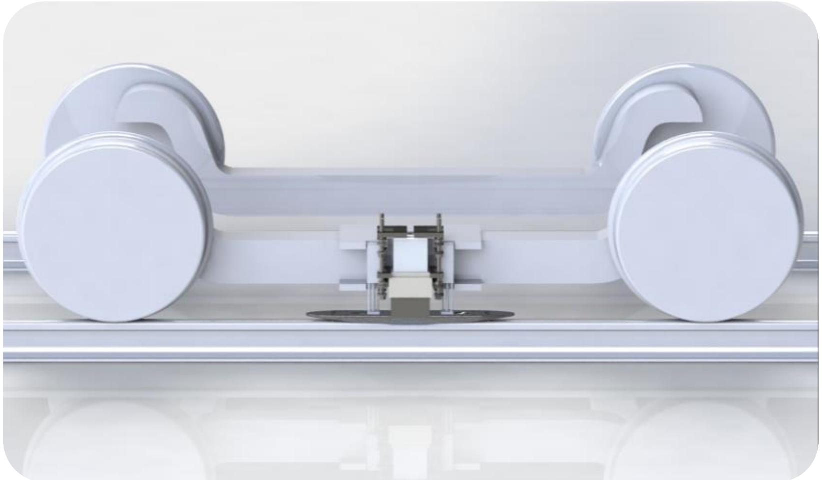

THE LASERTRAIN

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Date: 01-10-2018

No More Slippery Tracks!

LaserTrain information document

Laser Precision Solutions (LPS) is happy to work on solving slippery tracks on railway networks worldwide. We spend our entire day focusing on railroad slipperiness and how to get rid of this issue. As such, we have built up extensive knowledge on the topic that we are sharing in this document. This information document provides a concise overview of how we eradicate slippery tracks with the help of our LaserTrain, which will be live on the US railway track in the Autumn of 2018. The table of contents for this document is as follows:

1. Origins of the slippery railroad 1
2. What is slipperiness? 2
3. Impact on passenger transport..5
4. Our solution: The LaserTrain 7
5. Development plan 9

In section 1, we will set out the background to the most recognizable challenges that railway companies face worldwide. Section 2 explains the physics of slipperiness. Highlighting this information brings us to the impact that slipperiness has on the operation of passenger trains, which is addressed in section 3. Section 4 will then describe how these challenges can be tackled with our LaserTrain. In the last section, we show how our project plan for the LaserTrain, now and for the future.

1. Origins of the slippery railroad

Railway transport found its first application in the mining industry. The railway track was made from wood and in these days a horse was used to pull the cars. The big advantage was that the wheels experienced a very low rolling resistance, which made it easier to transport lots of heavy cargo in just one shipment with very little horsepower. This low rolling resistance suddenly became a problem when locomotives were used for propulsion in the 1800s: Low rolling resistance meant low traction and thus acceleration and braking proved problematic on slippery tracks. Railway operators all over the world are currently still challenged by this factor.

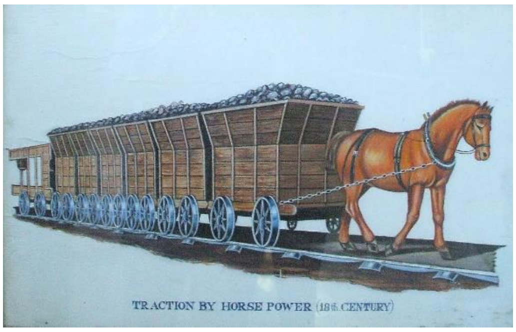


Figure 1: The origins of the railroad: Horses pulling mining carts on railway tracks

Railway operators made numerous attempts to counter this problem over the years. A sand spreader was introduced to increase friction and is still in use by train operators these days. Other methods include high pressure Waterjetting and Sandite. All the options that are in use today have several limitations. Most have a low operational speed making it difficult to deploy the system during normal operation. On top of this they require bulk material in the form of sand, water or coatings that require refilling, are costly and put stress on the ecosystem. The main problem though is that none of these methods are a real solution that fully cleans the track in a way that benefits the entire network. Railway operators continue to face punctuality issues, flat spots on wheels, capacity problems, safety issues and increased energy consumption because of the slippery tracks.

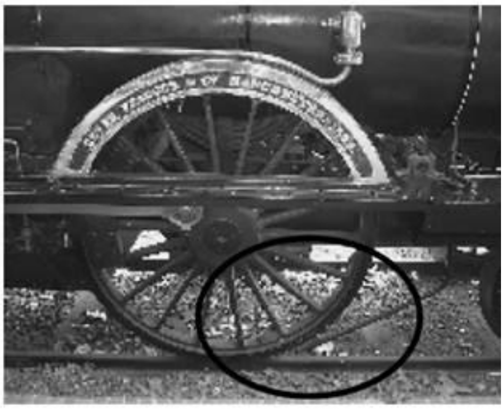


Figure 2: Sand spreader mounted on type 4.4.0. steam locomotive (1862)

To find a solution to this age-old problem, it is important to know more about slipperiness and the traction that can be used to move trains forward.

2. What is slipperiness?

To get a train in motion a force is required. This tractive force between the train wheels and the rails determines the level of acceleration and deceleration of a train. This wheel-railway friction is defined as 'the friction between a driven wheel and the surface it moves on'. Both a train's acceleration and its deceleration are limited by the friction available, which is expressed by the so called 'Coefficient of Friction' (COF), being defined as the ratio of the maximum available friction force (F_f) and the normal force (F_N):

$$\text{COF} = \frac{F_f}{F_N} \qquad (1)$$

This means that if the track has a COF=0.2, 20% of the axle pressure (say 60kN) can be used to propel a train forward (giving a maximum traction force of 20%*60kN = 12kN). The COF between train wheel and railway is influenced by various factors, the autumn leaf problem is the most notable one.

When leaves or other contaminants stick to the track and are crushed by train wheels they become a layer of oil acting as a lubricant which makes railways slippery by reducing the COF to a too low level. Train drivers cannot accelerate as quickly as normal and this results in increased stopping distances and longer acceleration times, leaving train drivers with no other option than lowering their speed.

Figure 3: Efficient driving depends on the slipperiness (COF) of the surface

> *The contamination layer is usually composed of various types of leaves, mostly a mixture of lignin, water and iron oxides. As well, it has been noted that other air-pollutants are able to cause a similar contamination layer, due to the pollutions settling on that track it sticks on the oxide layer. Together with the humidity or rain, a similar contamination layer is formed with specific characteristics.*

Wheel-rail contacts are rolling contacts and wheel slip is required in order to create a tractive force. The peripheral velocity of the wheel is comparable to the total velocity of the train within certain limits. That velocity between two moving surfaces (in this case the train wheel and the railway track) are to be considered as a superposition of pure rolling and pure sliding motion. The slide to slip ratio can be defined in terms of the sum velocity and the difference or the sliding velocity (2):

Figure 4: Wheel slip is required for traction

$$S = \frac{2\,|\,v_1 - v_2\,|}{v_1 + v_2} = \frac{2v^{diff}}{v^+} \qquad (2)$$

Where:

$v^{dif} = |v_1 - v_2|$

$v^+ = v_1 + v_2$

From rolling only ($v_{train} = v_{wheel}$) to simple sliding ($v_{wheel} = 0$ and $v_{train} \neq 0$) the COF would increase from zero (rolling only) up to a friction caused by shearing corresponding to the considered lubrication (contaminated) situation.

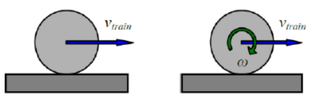


Figure 5: Simple sliding vs. rolling / sliding

A traction curve represents the COF evolution by varying the slip whilst keeping the sum velocity constant. Another dependency regarding the COF is given by varying the rolling velocity between the wheel and the railway at constant slip. Once increasing the velocity, the COF will decrease due to the wheel lifting off as a result of the pressure built up within the contamination layer. Together this variation, i.e. COF as a function of the sum velocity forms a so-called Stribeck curve.

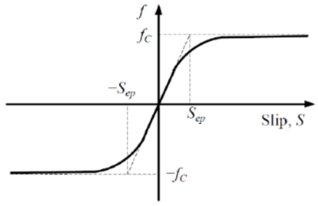


Figure 6: A traction curve

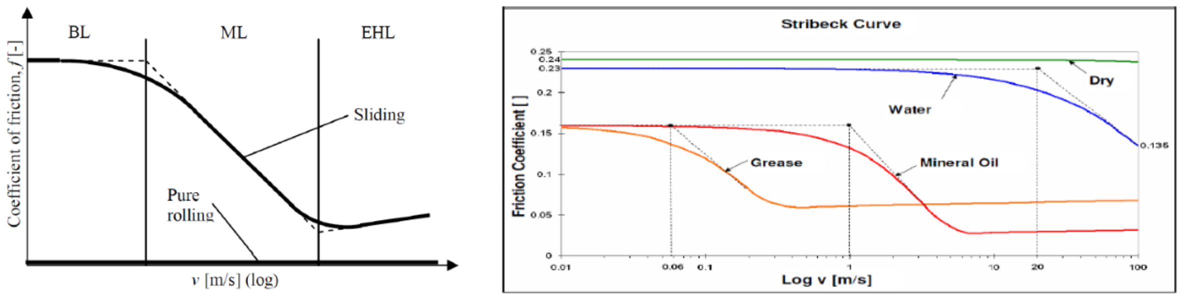


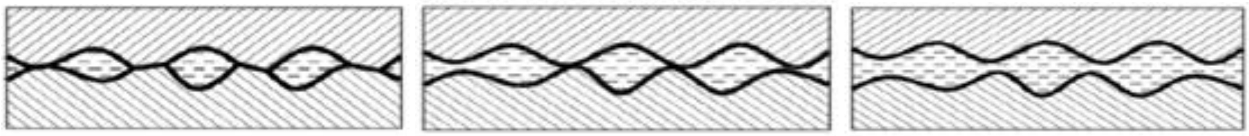
Figure 7:

Left: Stribeck curve for lubricated contacts *Right: Stribeck curve regarding different lubricants*

In the generalized Stribeck curve for lubricated contacts, three lubrication regimes are to be distinguished:

I. The boundary lubrication (BL) regime: at low velocity the load is carried solely by interacting asperities of the opposing surfaces and friction is controlled by shearing the surface layers present on these solid surfaces;
II. The elasto-hydrodynamic lubrication (EHL) regime: at high velocity the load is carried by the pressure generated within the lubricant (in this case friction is controlled by shearing the lubricant);
III. The transition regime between these two lubrication modes is represented by the mixed lubrication (ML) regime where the load is carried by the interacting asperities as well as the pressure generated in the lubricant.

These three options are schematically displayed in the figure below:



Boundary lubrication (BL) *Mixed lubrication (ML)* *Elasto-hydrodynamic lubrication (EHL)*

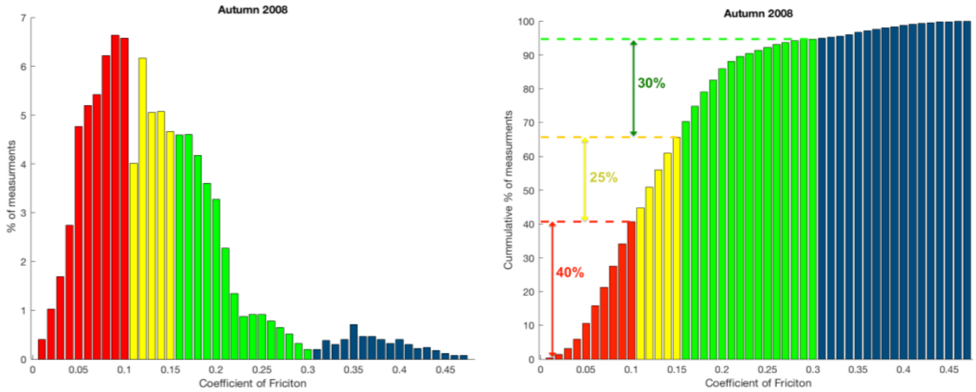
Figure 8: Three distinguishable lubrication regimes

The friction force in EHL lubricated contacts is caused by shearing the lubricant. In BL the friction force is caused by shearing the boundary layer located between the contraction asperities. The level of friction is expressed by the so-called 'shear rate' γ, defined as:

$$\gamma = \frac{v^{diff}}{h_c} \tag{3}$$

In this formula, h_c represents the film thickness. Reducing the film thickness will result in an increased shear rate and, as a consequence, in an increased *COF*.

A study carried out by R. Popovici in 2010 performed (using a basic tribology indicator) is one of the few conducted studies on the slipperiness of railroads. In autumn 2008 a series of tests were conducted on the Dutch railroad. At least 65% of the tracks measured had a COF lower than 0.15. Railway companies indicate a minimal COF of 0.15 to schedule trains efficiently. At lower levels of COF the track is too slippery and attaining the operational speed is problematic. Studies indicate that in the autumn of 2008 an astonishing 40% of the measured tracks had a COF below 0.10 causing severe safety concerns.



- Safety concerns
- Punctuality issues
- Optimal
- Increased wear-and-tear

Figure 9: The friction probability density on the Dutch railroads in the autumn of 2008

The inability to achieve a speed is because the acceleration or de-acceleration is governed by a simple formula:

a = COF * g

This implies that with an acceptable COF of 0.15 a train can accelerate with 1.47 m/s² (3.28 mph/s)
Given a cruising speed of 38 m/s (85mph) a train has an optimal deceleration time of 25.8 seconds with an average speed of 19 m/s (42 mph) and thus travels a distance of 490 meters (0.3 miles).
A train at that speed has a minimum stopping distance of 700m (0.43 miles) at a COF of 0.10. Below this a train should decrease its top speed. When a train isn't driven on all available axles the formula changes to:

a = COF * g * (Drivenaxles/Nondriven axles)

*<u>*Note</u>: In order to measure the COF a tribometer needs to be used, which should be similar to a train: The contact material (steel), the pressure (train) the surface area (wheel) and the speed need to match to measure the COF fully. The study by Popovici was the closest experiment to a full train tribology test ever done on the rail road, but lacked the full pressure of the train wheel as it was done with an extra wheel that was pushed down under a train. A real measure of the slipperiness can be performed using the LPS Tribometer.*

3. Impact on passenger transport

As the study by Popovici shows, a low COF during the autumn season is not an isolated incident, but a rather serious issue that happens within the entire network. It decreases the maximum levels of acceleration and deceleration and this puts stress on the entire network. Falling leaves during autumn are so problematic that slippery railroads are often referred to as the 'autumn leaf problem', but railroads around the world have their own set of issues with slippery railroads year-round. Examples are rusty tracks after storms, where the rust creates a contamination layer and blossom which has the same effect as a leaf on a track.

Figure 10: Slippery tracks are caused year-round by several distinct factors, each creating their own contamination layer.

We can group the issues arising from slippery tracks into the following five main areas:

Safety issues

- The mulch layer on the railway track forms an electrical insulation layer resulting in undetectable trains;
- This layer also causes low COF levels on railway tracks and train drivers are not able to break at a sufficient rate. Signal Passed at Danger (SPADs) and coming to a halt passed the station are the results.

Maintenance issues

- Low COF levels on railway tracks cause the wheels to slip and slide resulting in flat spots;
- These flat spots pounce continuously onto the railway track when driving and damage both railway track and train wheel further.

Capacity issues

- Low average speeds between rail stations has direct impact on the maximum capacity of the network. On busy networks delays cause a domino effect and train operators are forced to skip some trains from the time-table in order to prevent bigger problems;
- The extra maintenance decreases the availability of the rolling stock, creating a shortage;
- Maintenance on the railway track leads to disruptions, rerouting and alternative transport, which puts stress on the rest of the network.

Punctuality issues

- A low COF decreases the maximum level of acceleration of trains;
- A low COF decreases the maximum level of deceleration of trains;
- This creates a domino effect of delays for trains in a busy network, leaving passengers waiting longer at railway stations.

Energy consumption

- Train wheels require a small amount of wheel slip to provide a tractive force. At low levels of COF there is more wheel slip to deliver the same force. This extra wheel slip creates heat which is a direct energy waste;
- The slower acceleration means trains spend more time accelerating and less time at cruising speed. The most efficient method of driving is hitting cruising speed as soon as possible and then letting the train roll out to the next station, this is no longer possible with low **COF;**
- In order to reach the next station in a timely manner, it is required to brake and even with regenerative braking there is a loss of energy.

To illustrate how this all happens we look at how slippery railway tracks are addressed by most railway operators. During autumn most train operators adapt their capacity, either directly or as the result of imposing speed restrictions in the network. These actions are necessary in the autumn period, when the number of passengers hits its yearly peak. The result is that more passengers need to be cramped into fewer trains, creating unhappy passengers and longer loading times. When every stop takes a few seconds or up to minutes longer, train drivers feel the need to catch up between the stations. Slipperiness is preventing them from doing this and being in a hurry makes it worse: Effectually they are driving on ice, with a lower COF of the railway track than what they are accustomed to. This means the maximum acceleration is lower than normal and thus trying to accelerate faster than the COF of the railway track (since you are in a hurry) means creating a lot of wheel slip.

Wheel slip not only damages the track and wastes energy, it also decreases your acceleration – think of a car doing a burnout. This means cruising speed is reached much later and trains fall behind their schedule. If a train driver were to attempt making up for this time by braking late, the low COF of the railroad causes another problem: The maximum deceleration is lower than normal. A train driver hits the brake fully and normal engine braking does not stop the train as quickly as desired. More brake pressure causes the wheels to slide and the Wheel-Slide-Protection systems registers that it needs to release the brakes. At the same time, the system registers that it is not slowing down at the required speed and the full-axle braking joined with magnetic braking is activated. This locks the wheels, creating a lot of wheel slide and damages both the railway track and wheels.

The train driver reports an area with a lot of slip-sliding and the technical department needs to deploy their cleaning services. This same technical department also needs to true the wheels, repair the railway tracks and help with the safety inspection that likely arose from a Signal Passing At Danger from this problem with slipperiness. This common autumn cycle is visualized below.

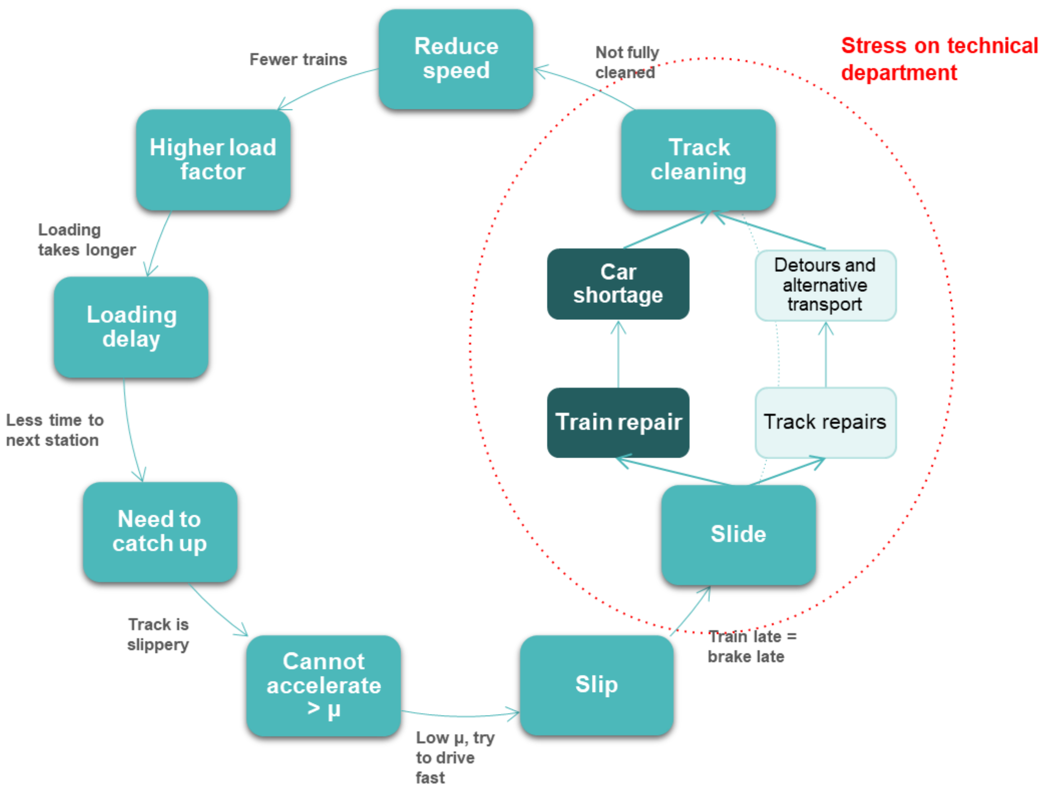


Figure 11: A common autumn cycle for railway operators

4. Our solution: The LaserTrain

After extensive testing we are now able to offer the LaserTrain (LT), which cleans the contamination layer off railway tracks with high-intensity lasers. By removing this layer, the level of friction can be kept in the optimal state year-round. This needs to be done at high speeds to increase the ease of operation and the efficiency of the cleaning in general. After applying the LaserTrain, the common autumn cycle for railway operators does not apply anymore.

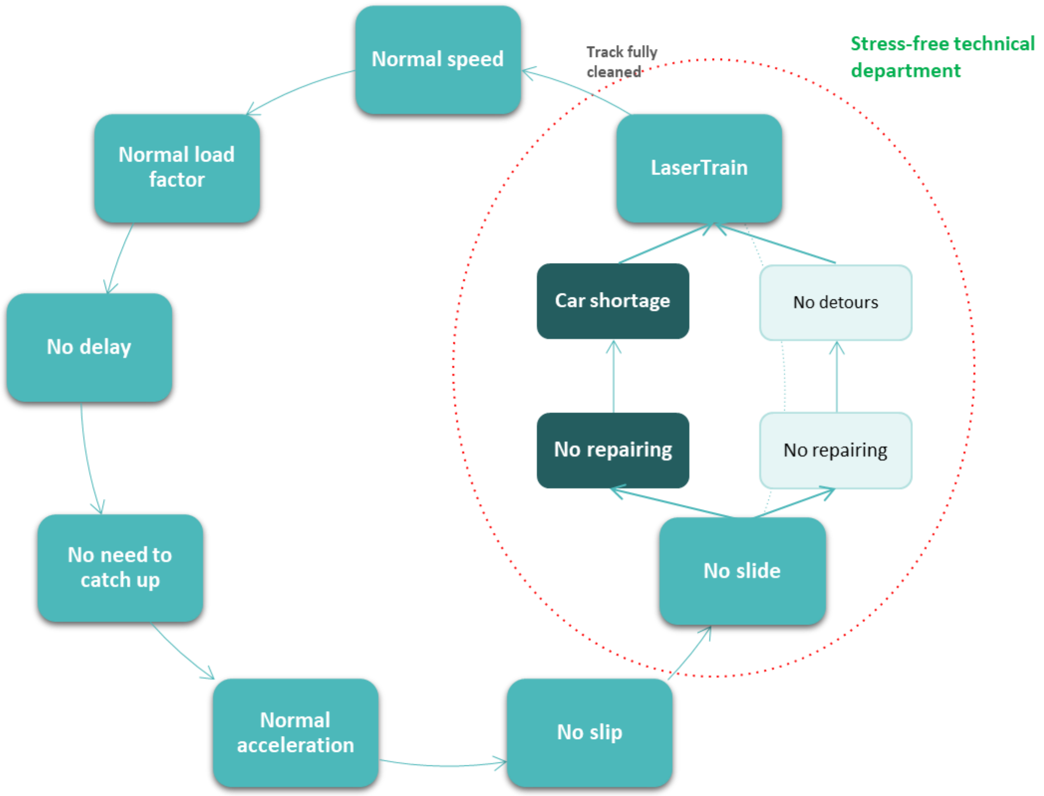


Figure 12: The new autumn cycle for railway operators using the LPS LaserTrain

The effects of this new cycle can be grouped into five distinct fields, which align with the most important KPIs for railway operators. Cleaning the railway track properly allows for faster acceleration and braking, prevents slip-slide and all the ensuing maintenance issues, is more energy efficient and improves safety at the same time.

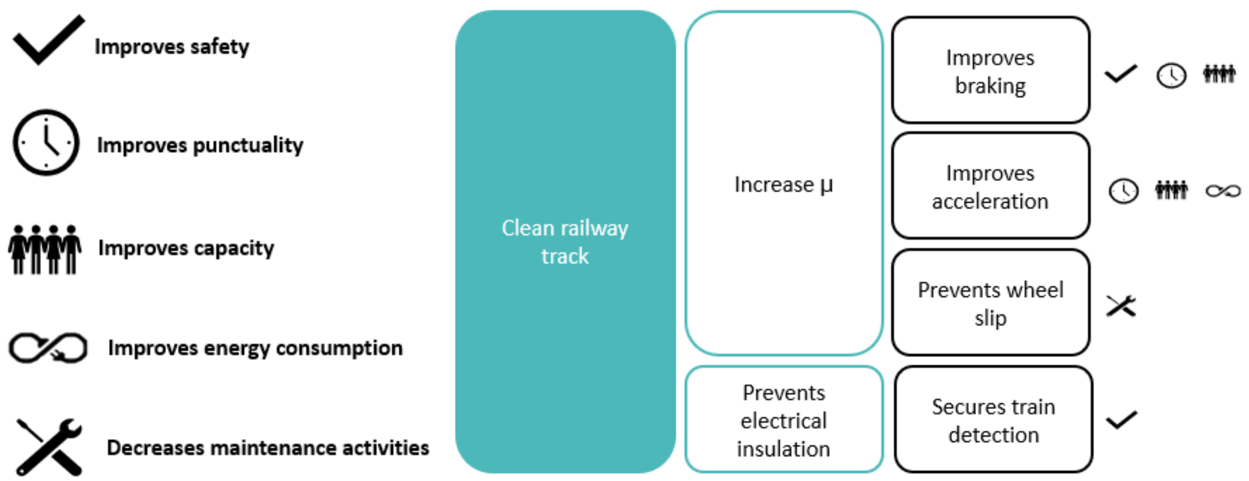


Figure 13: The benefits of using a LaserTrain on railway tracks highlighted in five important KPIs for railway operators

In order to understand the efficiency of the LT we need to look at how it works. The process of removing the contamination layer is called laser ablation. This specific technique has already been successfully applied within the fields of automotive, aviation, the transistor industry and art restoration. Laser ablation works in the following way: First, a high intensity laser pulse is focused on a certain surface, rapidly heating and ionizing the material by radiative heating. The material will either vaporize or sublimate. The ablation process is governed by characteristics of the ablation laser such as its wavelength, fluence, pulse duration and both the optical and thermodynamic properties of the substrate material and contamination layer.

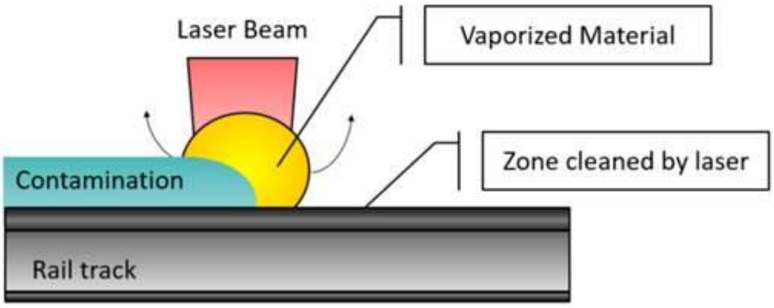


Figure 14: The principle of laser ablation

The most important laser parameter governing the effectiveness of the ablation process is the energy density, known as fluence (J/cm2). If the fluence is below a certain threshold, the ablation threshold, the material will not heat up sufficiently in an instant and thus will not vaporize. Above the ablation threshold vaporization will occur. In case of the autumn leaf problem, the ablation threshold of the contamination layer is much lower than the ablation threshold of the railway track. This makes it possible to remove the slippery contamination layer from the railway track without causing any damage to the railway track itself. To do this, the system is designed in such a manner that the fluence is above the ablation threshold of the contamination layer but significantly lower than the ablation threshold of the rail. As there are many different pollutants and hence many different contamination layers, the properties and hence the ablation threshold is different for many materials. After several months of testing, we can immediately identify which kind of layer requires what level of fluence. This way we can guarantee a fully cleaned railway track without damaging it.

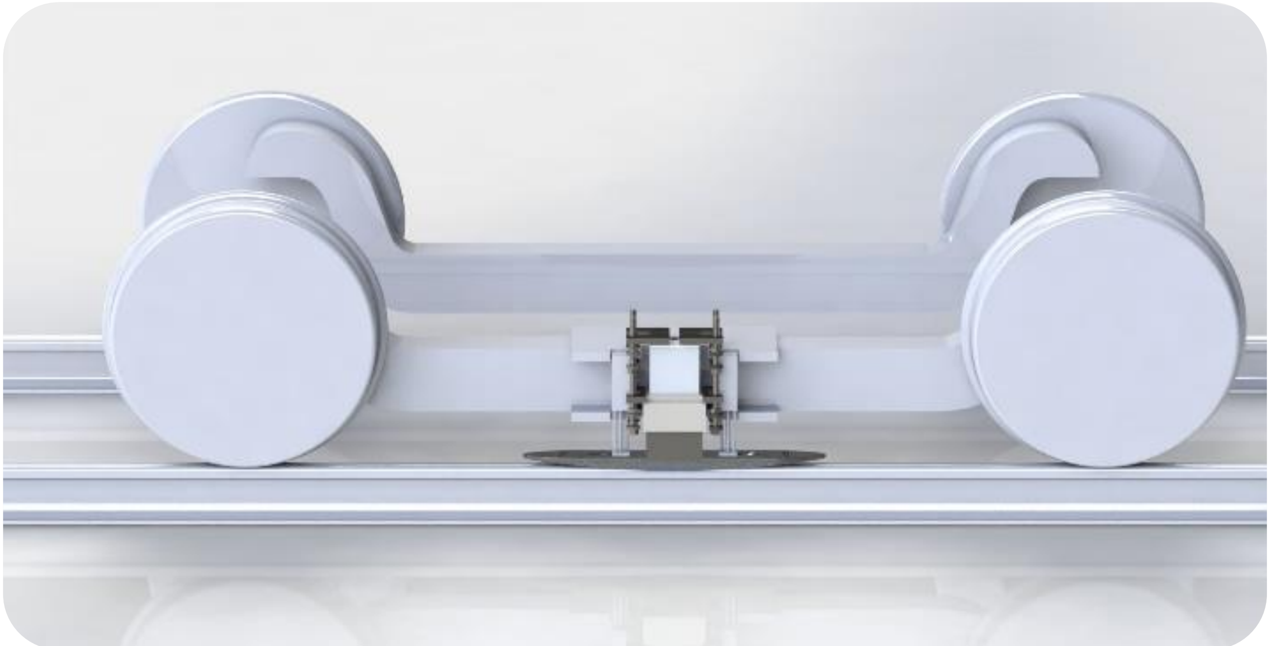


Figure 15: Design of the LaserTrain

5. Development plan

In 2016 LPS started with an extensive research and development plan, divided in 6 steps to work from the pilot version to improve the speed, safety and result. These steps are **(1) Maximize laser efficiency whilst cleaning a rail; (2) Measure the slipperiness of a track in (un)contaminated conditions; (3) Optimize Laser cleaning process; (4) Optimize laser safety; (5) Technology demo and (6) Prototype.** Step 1-3 have been completed successfully in 2016 and 2017 and together with our US customer, the last steps are taken in 2018.

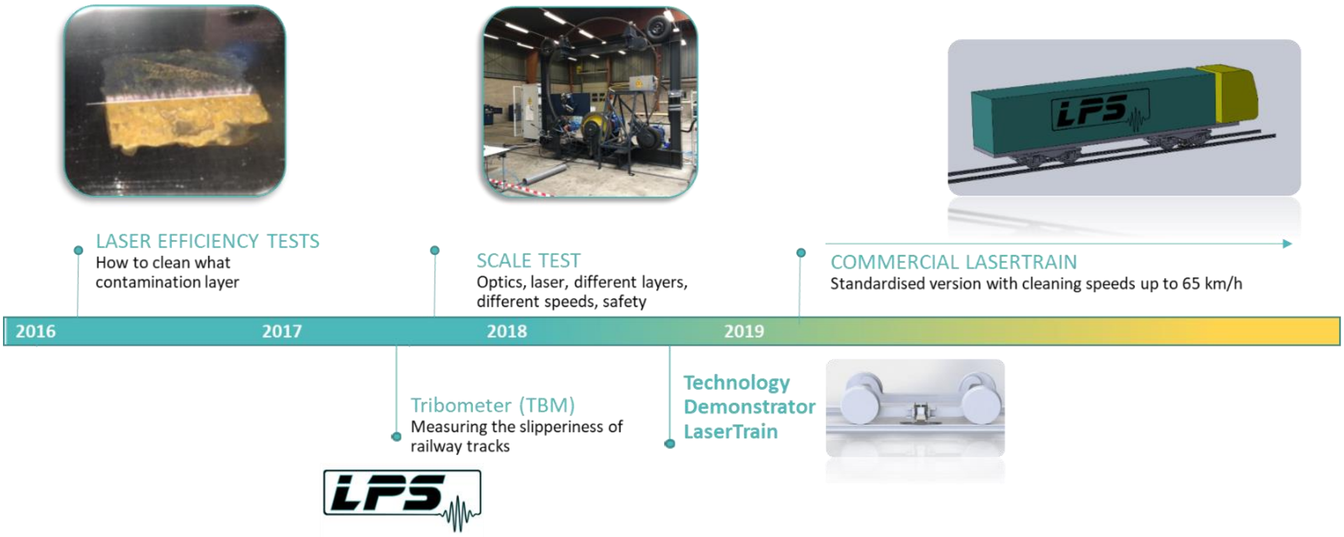


Figure 16: General development of the LPS LaserTrain

LPS is currently developing a LaserTrain prototype with the goal to make the solution so slippery railway tracks 'service proven'. The prototype is a scaled down version in terms of speed (which directly relates to cost) by reaching cleaning speeds up to 15 km/h. To not hinder further operation of the train network, the LaserTrain can speed up when necessary and cruise to designated areas.

For 2019 onwards, LPS is developing a standardised version of the LaserTrain that will be used in combination with a multi purpose vehicle. All LaserTrain equipment will be fitted in a 40 feet container, whereas the containment box will be mounted under the bogie. This setup allows LPS to easily install the LaserTrain for all interested clients worldwide and shortens the lead time of our cleaning system.

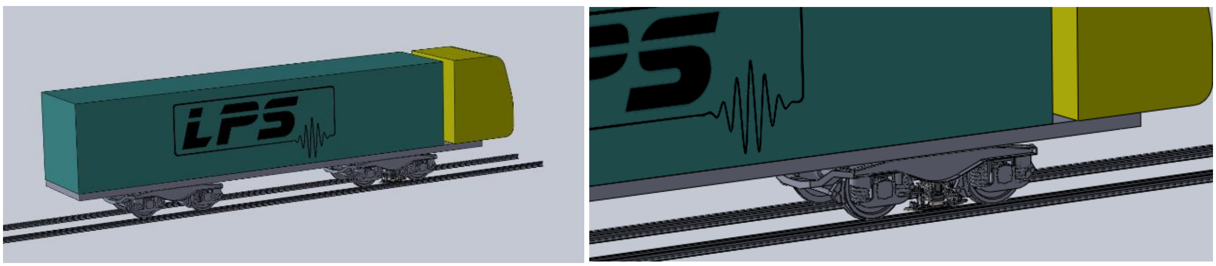


Figure 17: Standardized LaserTrain mounted on a multi-purpose vehicle

The LaserTrain is suited for at least 8 hours of cleaning per day which gives the results showed in Figure 12. Because of the possibility to vary with laser power, LPS is designing three versions of the standardised LaserTrain from 2019 onwards:

- **15km/h**: for cleaning large switchyards
- **25 km/h**: For cleaning dedicated lines
- **65 km/h**: For cleaning nationwide networks.