Space on the Line

If you were dozing on a long train journey and heard an announcement that your train was delayed due to space weather, would you think that you were dreaming of a problem with the Red Planet Express to Olympus Mons? Or would you just shake your head and add it to the list of eye-rollable railway problems, alongside weather that is too hot, too cold or too wet, the wrong kind of snow, leaves on the line, and so on and so on? Well, the truth is, space weather isn't some science fiction invented to hike your season ticket price: it affects railway systems around the globe, and I have been studying its effects on railway signalling systems in the UK. Space weather refers to the physical conditions and phenomena that occur in the space environment, particularly near Earth, that can affect technological systems and human activity in space and on the ground. An important part of space weather is geomagnetic storms, which occur when emissions from the Sun, such as coronal mass ejections (CMEs), disrupt the Earth's magnetic field. These storms can cause power outages, disrupt satellite communications, and lead to misoperations in railway signalling. The Carrington Event was a massive solar storm that occurred in September 1859. The event caused widespread disruption to telegraph systems, with some operators reporting sparks and fires, and others able to communicate with their power supplies turned off, purely by the currents that were being induced in the telegraph wires by the storm. Auroras were observed as far south as the Caribbean; they were so bright that they sparked an argument among gold miners in the Rocky Mountains as to whether it was time for breakfast. More recently, in March 1989, a powerful geomagnetic storm caused by a CME disrupted power grids in Quebec, Canada. The storm caused a power surge that triggered plant safety systems and over six million people lost power for several hours. While the Carrington event may not have been too damaging in the mid-1800s, today's society depends far more on technology and the risk that severe space weather poses has increased significantly. The potential risk to railway systems comes from electrical currents induced in the ground and in long conductors such as power lines, oil pipelines and railway lines, and the signals that control train movements.

Railway signalling

There are many types of railway signalling systems, but most follow the same basic setup: a train line is split up with insulated joints in the rails to form multiple smaller sections called 'blocks'. Only one train can occupy each block at any time, and various detection methods are employed to let train drivers know if the blocks in front of them are occupied or not. One widely used detection system is the 'track circuit', shown in figure 1. A power supply is placed at one end of the block and a relay is placed at the opposite end, so that currents travel through the rails from one to the other, contained in their block by the insulated rail joints. With no train occupying the block, the power supply energises the relay which displays a green signal to oncoming drivers; when a train enters the block, the conducting wheels and axles cause a short circuit, and the current from the power supply no longer reaches the relay and it de-energises, displaying a red signal. The reason that the default state of a track circuit is the energised state is to act as a failsafe. If there is a malfunction anywhere in the circuit, the relay will de-energise and show the block as occupied, avoiding potential collisions. The UK has both unelectrified and electrified railway lines. In the unelectrified case, the insulated rail joints are usually located at symmetrical positions in both rails. This means that the currents induced in both rails from geomagnetic storms are equal, and no induced current will cross the relay, effectively making them immune to interference from space weather. However, in the case of electrified lines using alternating current, there needs to be a continuous path for the current from the overhead lines that power the train to return to the power grid. This is achieved by removing the insulated rail joints from one of the rails (the traction rail), allowing it to carry the current from the train back to the grid to complete the circuit. This is where space weather enters the picture. The electric field generated at ground level during geomagnetic storms can induce a current in the rails that either flow with or against the existing current in the track circuit, interfering with normal relay operation. These additional currents can potentially de-energise an energised relay, making it seem like the block is occupied when it is not (a right-side failure), or energise a de-energised relay, making the block seem clear when there is a train occupying it (a wrong-side failure). Such failures are called misoperations.

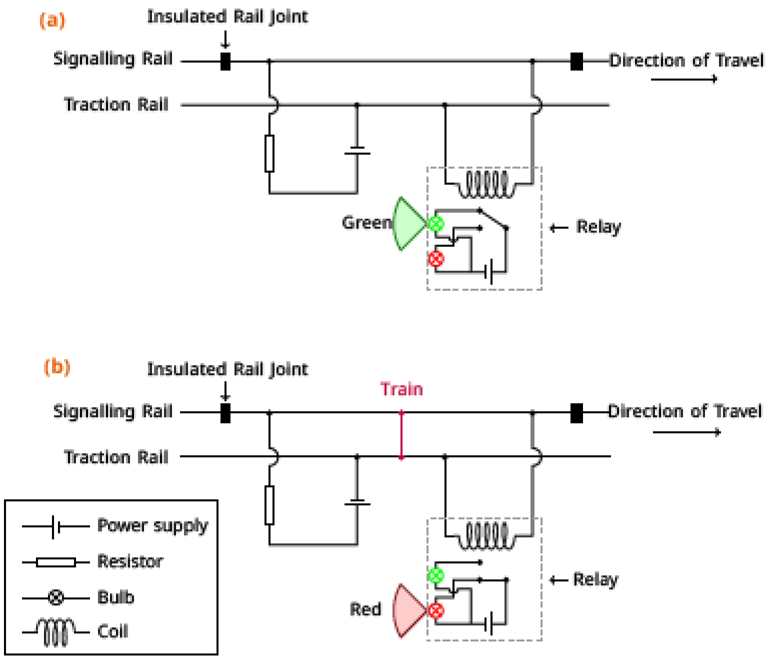

Figure 1. Diagram of a railway signalling track circuit. (a) shows an unoccupied block. The current from the power supply (left) reaches the relay (right) and energises it, causing a green signal. In (b), the block is occupied. The train is causing a short circuit, current from the power supply no longer reaches the relay, causing it to be de-energised, displaying a red signal.

Making models

I have created realistic models of two railway lines in the UK: a north-south orientated portion of the West Coast Main Line between Preston and Lancaster, and the east-west orientated Glasgow to Edinburgh via Falkirk line. In this model, each rail is regarded as a transmission line consisting of series impedances and parallel admittances that correspond to the resistance of the rails and the leakages to the ground, respectively. Subsequently, the transmission line model for each rail is transformed into an equivalent-pi circuit, comprising admittances and current sources, as described by Boteler (2021). The resulting circuits for both rails are then combined with the track circuit relay components to establish a nodal admittance network. Data from Network Rail standards documents were used to ensure the model parameters were relevant to the UK. In this article, I am only going to discuss the Glasgow to Edinburgh line, shown in figure 2. For simplicity, I am only considering right-side failures, the case where no trains are occupying any blocks, and the problem is the de-energisation of energised relays. Patterson et al. (2023) contains a more detailed explanation of the model and further results not discussed here.

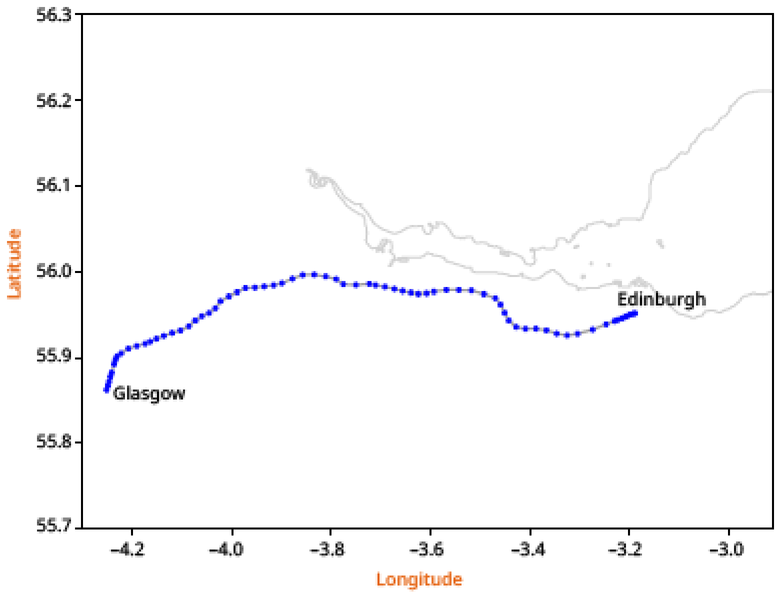

Figure 2. Map of the Glasgow to Edinburgh via Falkirk line. The line has been split into blocks, with the dots representing the boundaries of the track circuits.

Thresholds for misoperation

To understand what happens to the current through the relays during a geomagnetic storm, first consider the case where there is no geomagnetic activity. In the model, the external electric field was set to zero, so no currents are being induced in the rails; the only currents are those from the power supplies. Figure 3 shows the current through each of the relays along the line. The red (solid) line indicates the 'drop-out current', the value that the current through the relay must drop below to de-energise. The green (dashed) line shows the 'pick-up current', the value the current must go above to energise once again. Under these conditions, all track circuit blocks should be energised, which they are. As an aside, the gap between the drop-out current and pick-up current is an important factor. If the induced currents in a track circuit force the relay to de-energise, it has to then go above the 'pick-up current' to re-energise. This means that once the relay misoperates, even if the induced currents responsible fall, the misoperation could persist. Raising the electric field by 0.1V/km at a time, we are able to pinpoint the threshold at which the first misoperation occurs. In this case, the first relay misoperates when the eastward electric field is reaches –2.8V/km, as shown in figure 4.

Based on the results of Beggan et al. (2013), an event of this magnitude in the area of the Glasgow to Edinburgh line is expected to occur once every 30 years. The electric field expected to arise from a 1-in-100- year extreme space weather event is estimated at around 5V/km for the UK. Let's take a look at the what the situation might be on the Glasgow to Edinburgh line under those conditions. Figure 5 shows that a geomagnetic storm of that magnitude would give rise to significant disruption, causing many of the signals across the line to misoperate.

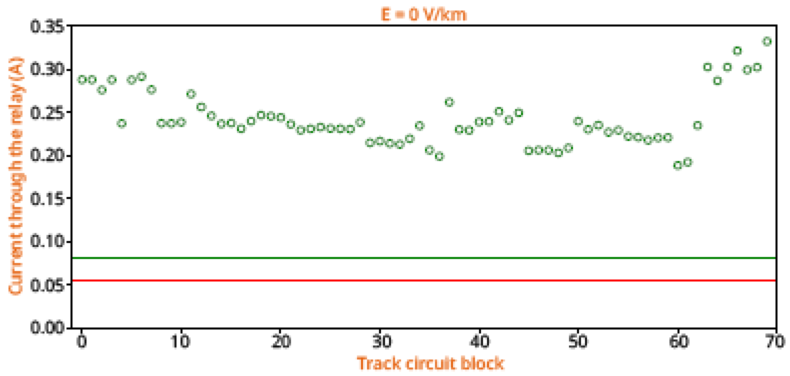

Figure 3. The current through each of the track circuit relays between Glasgow to Edinburgh with no geoelectric field applied. In this and the following figures, green circles indicate the current of each relay, the red (solid) line shows the current value below which the track circuit would de-energise and display an incorrect signal, and the green (dashed) line shows the level that the current would need to rise above to re-energise if de-energised. An unfilled green circle means normal operation, so in this case, all signals show no misoperations.

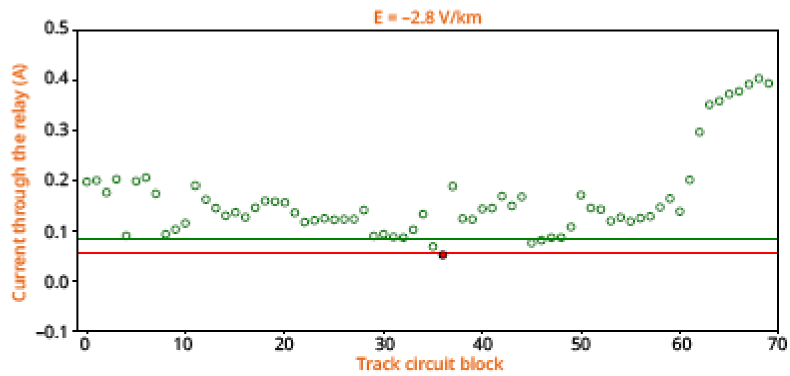

Figure 4. The current through each of the track circuit relays between Glasgow to Edinburgh with a geoelectric field of –2.8V/km applied. A filled red circle indicates a misoperation. In this case, we see the first misoperation for the line, at block 36.

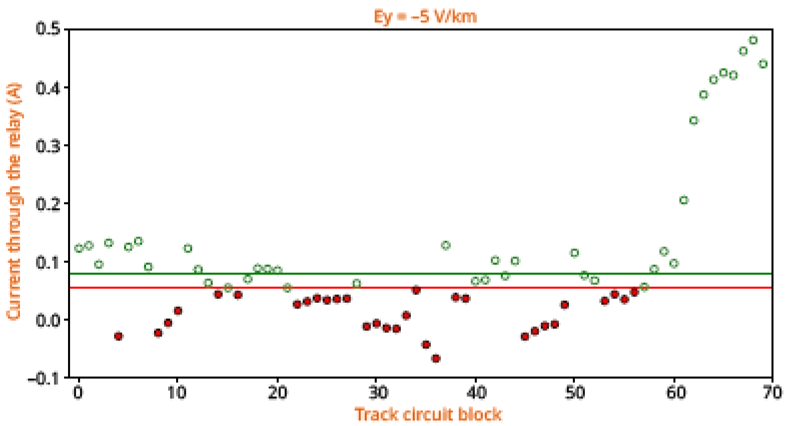

Figure 5. The current through each of the track circuit relays between Glasgow to Edinburgh with a 1-in-100-year geoelectric field estimate of –5V/km applied. In this case, the model shows many misoperations – red filled circles – all along the line.

What does this mean for us?

Right-side failures have the potential to be disruptive, but not hazardous. Signal operators would notice the signals turning red without a train occupying the block. As de-energisation is the default failure mode of a track circuit relay, this would present a similar scenario to other faults unrelated to space weather. Trains may be asked to proceed more slowly through the blocks in question, resulting in delays. Passengers should note that space weather seems to affect railway signalling far less frequently than many of the other issues that railway operators face daily. It is also worth noting here that signalling failures would not be the only problem in an extreme space weather event; it is more than likely that power grids, GPS satellites, and radio communication are all going to be affected simultaneously. We are no longer in the 1800s, where a failure in the telegraph system has little impact; the interdependency of the power, communications and transport systems is where the disruptive power of space weather lies. We must continue to research those areas, and ensure that we are prepared for the inevitable effects of space weather.