JAMES DYSON FOUNDATION UNDERGRADUATE BURSARY 2019/20

Project Summary

Background

Anyone who takes trains on a regular basis is all too aware that delays are commonplace; not only are they frustrating for the traveller, but they incur enormous costs for Train Operating Companies (TOCs), who offer reimbursement for significant delays.

The number of journeys has been rising for around 30 years (Figure 2). The increased traffic introduced must be at least partially responsible for the delay, but is it the only factor? Scaling the delay by the number of journeys, we see that it continues to rise (Figure 2); something else must be contributing.

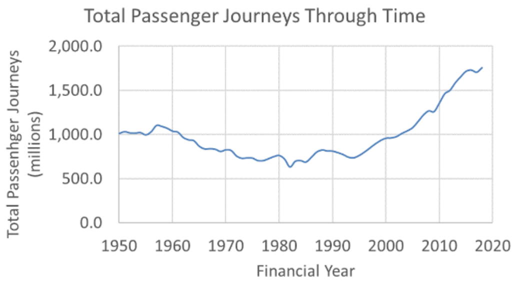

FIGURE 2: BRITISH PASSENGER JOURNEYS THROUGH TIME.

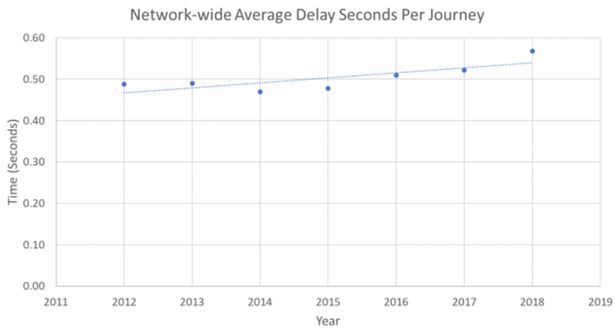

FIGURE 2: DELAYS SCALED BY NUMBER OF JOURNEYS THROUGH TIME.

Operational disruptions encompass delays occurring as a result of failures in infrastructure and operation such as signal failures and overrunning engineering works. Network Rail is liable for these delays, with them being classified as "Network Rail-on-TOC". Not only do these delays contribute significantly to overall delay, but their number has been rising significantly (Figure 3). Clearly there is an opportunity to reduce delays by focusing on operational disruptions. This project aims to achieve this by concentrating on early identification of a particular fault known as voiding.

Voiding Explained

If the ballast beneath the sleepers is worn or displaced (by water, for example), the cavity which remains is known as a void. These voids are rather troublesome as they can eventually induce other faults. With the sleeper unsupported it flexes into the gap, adding undue stress and fatigue to the rail to produce a crack. If this crack occurs between two sections of rail, at a block joint for example, the two become electrically connected, leading to incorrect reporting of trains' positions. Voids are particularly troublesome at Switches and Crossings (S&C), where the train can be made to travel along one of a range of tracks (Figure 5). If a void forms at the switch, the stretcher bar which keeps the rails at the correct distance can crack. At the crossing, voids can lead to damage of the crossing nose; both of these can increase the chance of derailment. To make

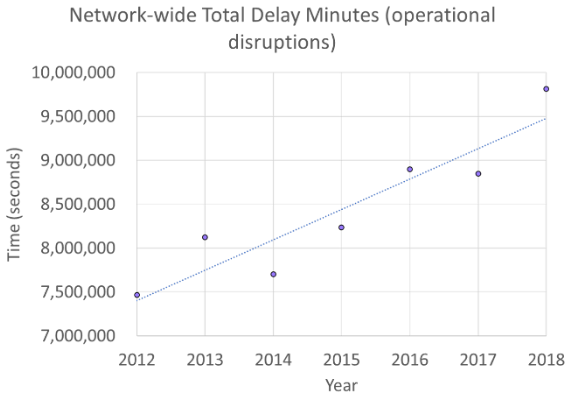

FIGURE 3: OPERATIONAL DELAY MINUTES.

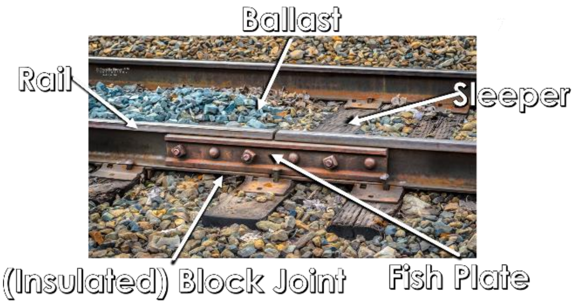

FIGURE 5: TYPICAL RAIL LAYOUT.

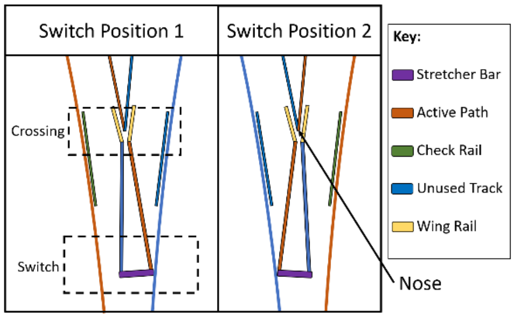

FIGURE 5: SWITCH AND CROSSING (S&C) LAYOUT.

matters worse, discontinuities in the track at block joints and S&C lead to high-impact loads which accelerate wear of the ballast, creating voids. Network Rail's current automatic void-detection techniques suffer from poor reliability; those that aren't automatic are more accurate, but use stationary sensors which must be placed beside the track once a void has been suspected. We ideally want a solution which is both accurate and reliable.

Frequency Decomposition

Consider a guitar; when we pluck each string we hear a different note depending on the tension applied by tuning at the neck and the thickness of the string. However, we also know that the same notes applied by different instruments such as an electric guitar, banjo or piano sound distinctively different. We also see that plastic guitar strings tend to give a warmer sound compared to metal ones. Why is this?

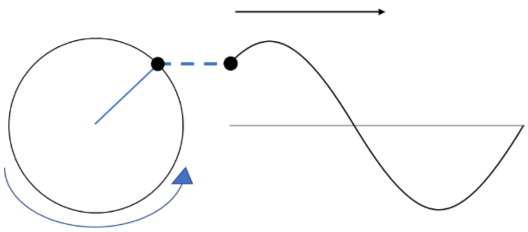

FIGURE 6: ROTATING PHASOR.

Joseph Fourier discovered that any function can be made by adding together a number of the most simplistic harmonic function we know – sine waves. We can make a sine wave by tracking a dot on a rotating circle (Figure 6); imagine spinning the circle and pulling the sheet of paper to the right as it draws. So to make the sine wave oscillate more quickly, we simply increase the speed at which the circle rotates and to change its amplitude we make the circle bigger or smaller. If we want to make a square wave we might match the peaks and troughs of our sine wave to the peaks and troughs of our square wave, but this is obviously quite a poor approximation! What about if we attach a smaller, faster rotating circle to our first? This time, we see smaller oscillations which "hold" the peak of our sine wave for longer and look closer to a square (Figure 8). If we add many more of these circles, our square wave slowly starts to appear.

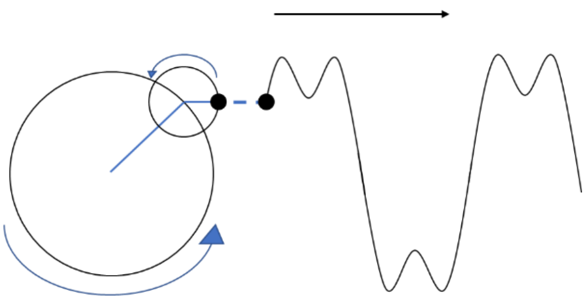

FIGURE 8: ROTATING PHASOR DEPICTION OF APPROXIMATE SQUARE WAVE.

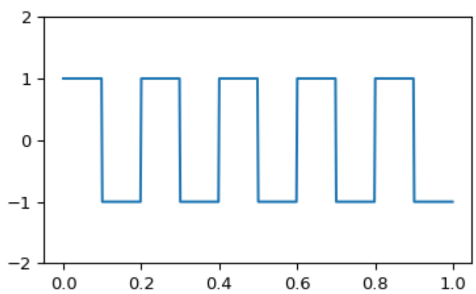

FIGURE 8: SQUARE WAVE.

The square wave is not special here, and any function can be made by adding these circles (sine waves) together. Of course we can then do the opposite; decompose a real sound wave into a sum of sine waves at different frequencies and amplitudes. Usually, there is a first frequency with an amplitude much greater than the rest, as with the large circle in our square wave example. This is known as the fundamental, and is responsible for the note we hear; the additional sine waves make each instrument sound slightly different, despite playing the same note. But why is this?

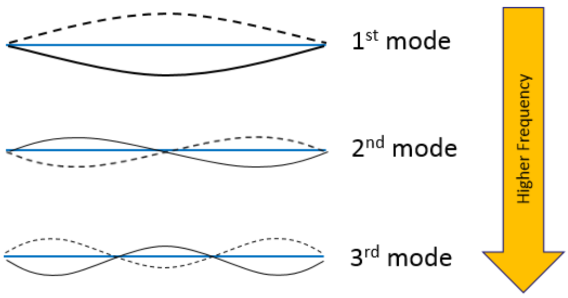

FIGURE 9: MODES OF PINNED STRING VIBRATION.

The sound wave produced by an instrument is a direct result of how that instrument vibrates, and this itself is dependent on the properties of the instrument; its shape and materials. This is why changing something as simple as a guitar string made of metal to one made of plastic can alter the sound so drastically.

A guitar string is a simple example; the fact that it is pinned at both ends means that only certain shapes can be formed, known as "mode shapes" (Figure 9). Each of these shapes therefore produce different frequencies known as natural frequencies. In reality, the complicated motion of the string is a summation of these modes, which is why we hear the fundamental first mode, along with a rich set of tones increasing in frequency but of lower amplitude.

Applicability to Project

When a train passes over a void, it excites the sleeper into the cavity, creating an audible vibration. If we can identify the note produced by an oscillating instrument both audibly and with machines, it stands to reason that the same could be used to identify the presence of a void, along with its size and shape.

Unlike a string, the sleeper is suspended partially along its length by the ballast, which will depress slightly (Figure 11). This behaviour was modelled as a set of tightly packed springs, the stiffness of which can be found by analysing the soil structure beneath (Figure 10). From here, a set of equations can be used to determine the function describing the oscillation of the sleeper when hit by a passing train. By knowing the properties of a typical sleeper (its size, shape and material), we can use this function to predict its mode shapes and therefore the frequencies of each sine wave which, when added together, produce the oscillation predicted.

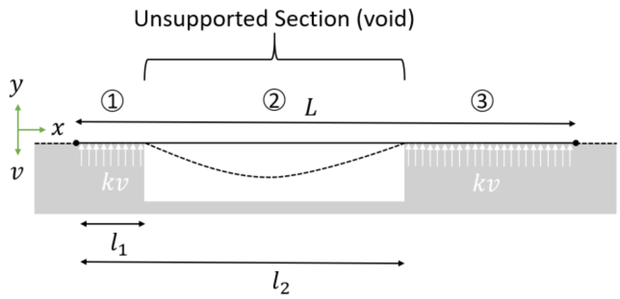

FIGURE 11: SLEEPER MODEL.

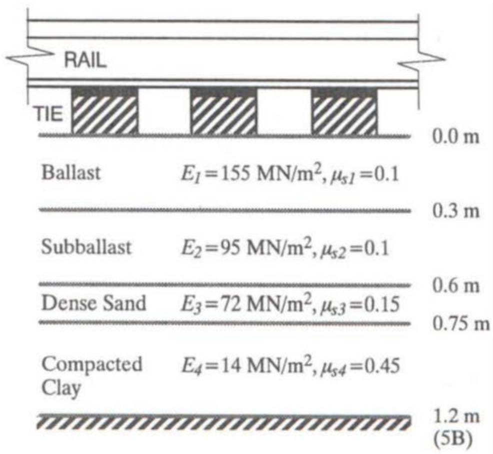

FIGURE 10: BALLAST MODEL.

To test the idea, a high-quality microphone, wind shield, tripod and recorder were used on railway sites to record sounds (Figure 12). A computer program was written which analyses the sound data and returns all of the frequencies contained within it, along with their amplitude; another program then removes noise from this signal and finds the peaks corresponding to each natural frequency (Figure 13).

FIGURE 12: RECORDING EQUIPMENT.

Conclusions

By comparing these frequencies to those predicted, it was possible to confirm that voids are detectable this way.

This method was also found to demonstrate some ability to predict the size and position of the void beneath the sleeper, given the frequencies found.

Next Steps

The spring stiffness previously mentioned is difficult to find accurately; it's affected by not only the soil structure, but the loading applied. One of the natural frequencies predicted is a function of the stiffness parameter, and is independent of void presence; it should therefore be possible to locally estimate its value by searching for this frequency across a range of sleepers. More data collection and analysis is required to test this.

Data collected this year records void presence only. In order to discover whether void size and location beneath a sleeper can be accurately measured, additional data is required with this information recorded.

Some of the data collected was affected by adverse weather; for a more accurate analysis, a greater quantity and quality of data is required.

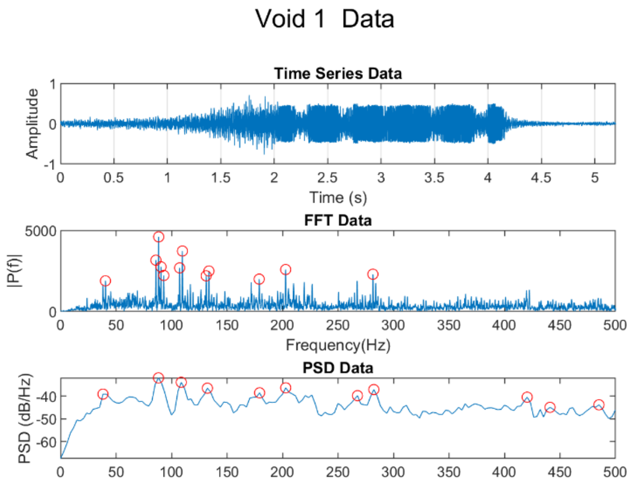

FIGURE 13: VOID DATA.