Identification of High-Speed Rail Ballast Flight Risk Factors and Risk Mitigation Strategies

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Abstract

With the development of high speed rail (HSR) systems around the world during the past 50 years, one of the observed phenomena that occur at the train-track interface is the "ballast flight", a phenomenon where ballast particles become airborne during the passage of a train. This phenomenon occurs when a combination of both mechanical and aerodynamic forces generated mostly by the passage of the train cause a ballast particle to overcome gravity. Factors affecting ballast flight include aerodynamic conditions, track response, ground effects and atmospheric conditions. Damages to the railhead, train body, and adjacent structures as well as injuries to maintenance staff have been reported in the literature to result in a major maintenance cost and safety concern for HSR systems with ballasted track. Previous studies have used laboratory wind tunnel tests and large-scale field tests to verify the various causes and mechanisms of ballast flight, and theoretical models have been developed to simulate the phenomena. However, there are only few existing practical risk models formulated according to certain field and/or analytical occurrences and used to assess the risk of ballast flight under different HSR operating conditions. For example the French National Railways (SNCF) and the Spanish Railway Administration (ADIF) have developed models to assess the flying ballast. A comprehensive literature review is needed to identify all the risk factors relevant to potential HSR operational conditions in the U.S. This would enable the development of a risk model to assess the ballast flight risk. The purpose of this article is to present the planned framework by the University of Illinois at Urbana-Champaign to perform a full evaluation of risk factors that may contribute to ballast flight in the United States where HSR is now emerging. This findings will likely to provide a basic strategic development plan for ballast flight risk for HSR operations in the United States. The scope of the work will include an identification of operating and infrastructure conditions that may lead to ballast flight, a development of risk assessments and methodologies for HSR planners and operators in North America, thus allowing the development of safe HSR systems.

1. Introduction

Since the 1960s speeds along the main railway lines worldwide have been increasing on a steady pace. Starting in 1964 with the opening of the Tokaido Shinkansen high speed line, true high speed rail has seen an increasing success in those countries where such lines were eventually built. While a HSR system is essentially a railway like any other, there are however differences that make a HSR line unique compared to conventional railways. Features such as very high radius of curvature, track centerline distances, are common in this environment. With the increase of the speed, however, much attention has been devoted to assure the highest safety and comfort levels possible. New train sets were conceived by designers such as Alstom or Bombardier where riding comfort is considered a top priority. Great attention has also been given to the track infrastructure. New track design was required to allow speeds beyond 300 km/h (186.4 MPH), thus implementations of slab track have been used quite extensively on new HSR tracks.

Ballasted track is still considered as the most cost-effective solution for not only conventional track but also for high speed railway operations. One of the main issues with the adoption of ballast as the main track support is its behavior at very high speeds. With the increase of the speed of the train beyond 260 km/h (161.5 mph), stones that are part of the ballast body were observed to have moved from their rest location (Agretti, 2012). The phenomenon at which ballast particles become airborne is called “ballast flight”. The consequences of such movements can vary from being negligible to catastrophic: one could just imagine a stone blown by the wind generated underneath the train, and hitting the train itself which is travelling at 300 km/h (186 mph). Possible damages can span across rail, track structure, immediate surroundings, and the train car. This article presents the high level conceptual analysis of ballast flight risk. A preliminary list of risk factors are identified and discussed in detail. Based on the current practices adopted by countries where HSR is in operation, a discussion of possible mitigation strategies is also presented. Finally, a semi-quantitative risk matrix framework is introduced.

2. Risk analysis

The phenomenon of ballast flight may be characterized by both the mechanistic and probabilistic design. This paper will mainly focus on the latter. The approach presented here identifies the factors

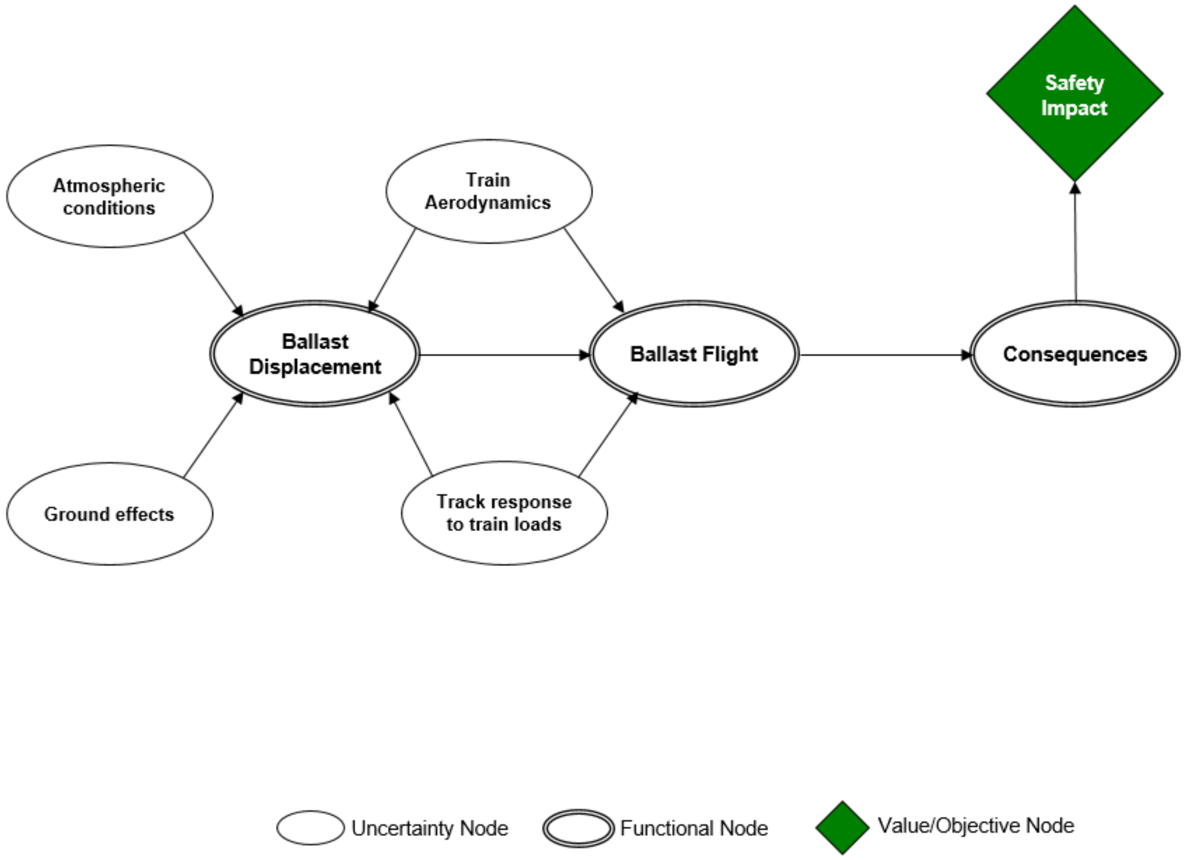

Figure 1 - Preliminary risk influence diagram for flying ballast

that can contribute to ballast flight, based on the literature reviewed. The probabilistic occurrence of a ballast flight event is modeled as a combination of two sub-events – the displacement of ballast particles and the ballast flight given the displacement. The likelihood of ballast displacement is affected by the atmospheric conditions and ground conditions, while atmospheric, track, ground and aerodynamic forces contribute to the likelihood of ballast flight given a ballast displacement. Shown in Figure 1 is an influence diagram that outlines the four major risk factors that may contribute to the overall ballast flight event. A brief discussion of the most relevant factors is presented in the following sections.

2.1. The concept of risk

One way to define the risk of flying ballast, R_{fb}, is through the following relationship:

$$R_{fb} = P_d \times P_{fb|d} \times C$$

where P_d is the probability that a ballast particle will displace from its rest position, $P_{fb|d}$ is the conditional probability that a ballast particle will fly given the displacement, and C is the consequence from the event of flying ballast.

To be able to estimate the probabilities described above, there is a need to understand the conditions at which flying ballast may occur. In the following sections, the major factors are presented and discussed in detail.

2.2. Aerodynamic conditions

Aerodynamics is one of the most important aspects studied related to train operations (Quinn et al. 2010). There have been extensive studies to understand the effect of aerodynamic forces acting on the track (Kaltenbach, 2008, Weise, 2012). The key aerodynamic factor is speed, since the aerodynamic force is proportional to the square of the speed of the train. Discussion with several HSR operators worldwide suggests that ballast flight have appeared to occur at speeds above 260 km/h (161.4 mph). Other factors to take into account in this first risk factor are aspects related to the train design. A different nose configuration of the front of the train might be the key difference in experiencing flying ballast. One factor that is considered important by HSR operators when attempting to characterize flying ballast is the length of the train. Studies performed in Spain as well as in Italy suggested that the length of the train played a major role in the initial displacement of particles (Agretti, 2012, and Lazaro, 2011). It was noted that ballast flight was more likely to occur with a double-composition train – two separate trainset units coupled to make up a longer train. This is due to the buildup of vortices underneath the car body of the train. While the length of a single composition train (8 cars) does not generate an aerodynamic pressure sufficiently high to displace the ballast particle, a 16-car composition is more prone to generate the phenomenon. This has been observed in Spain (Lazaro & Gonzalez, 2011) and Italy (Agretti, 2012). In addition, wheelset design directly relates to the trainset configuration. The important aspect to consider here is the design of the flange of the wheel. If a ballast particle is set into motion due to some of the factors described previously, the particle could then hit the tip of the flange, thus causing the projection of the particle.

While the speed of 260 km/h may be considered as a threshold value above which ballast flight may occur, there are other environments that may lead to the occurrence at lower speeds such as in a tunnel which itself imposes a boundary to the air flow generated by the train. It was noted that in tunnels where posted speed limits were around 140 km/h (87 mph), the sign posts appeared to have significant damage from objects hitting the signs at high speeds. One additional consideration related to speed is the effect of passing trains. There have been instances (FRA Accident Database, 2003) where a ballast stone was blown up when two trains travelling at speeds below 160 km/h (100 mph). In summary, speed is probably the most important factor to contribute to ballast flight and it has been reported by HSR operators that ballast flight occurrences are seriously limiting the ability of these operators to raise the speed on their lines. Lazaro et al. (2011) have performed a full scale experimental test to validate a risk model based on the speed of the train. It was noted that the likelihood of ballast being displaced from its “at rest” position would dramatically increase as the speed of the train went above 260 km/h (161.5 mph). Similar results were found in field studies performed in Italy (Diana, 2012, Rocchi, 2013).

2.3. Track response

Several research studies have explored the behavioral response of ballast subjected to the dynamic load of the train (Luo, Yin, & Hua, 1996). It was noted that under certain loading conditions, the particles at the surface of the track would become weightless, meaning that the reacting forces applied to the particle would be large enough to overcome any gravity forces. Closely related to the trainset design are the effects of the bogies. The distances between wheelsets and between bogies can change the load input frequency to the track, thus causing different responses of the track. Several models are available to characterize the response of the track structure due to the exciting loads imparted by the train. Models are accurate in predicting the behavior of track as a whole, but little information was found in attempting to explain the initiating mechanisms of ballast displacements.

Typically, HSR systems require the use of the best quality ballast. Most HSR operators in the world (SNCF, RFI, ADIF, etc. among others) require ballast to satisfy strict gradation specifications. Kwon & Park (2006) performed an analysis of ballast particles being displaced in a wind tunnel setting. They found that the size of the particle had a direct relationship with its likelihood to be picked up by winds. Specifically a particle weighing 50 grams (1.76 oz.) had a probability of 50% to be picked up by aerodynamic forces.

2.4. Ground conditions

It is important to consider the response of the sub-ballast and subgrade to loadings coming from the train as well as loadings produced by natural events, such as mild seismicity. Small magnitude earthquakes, while not felt directly by humans, can on the other hand produce an input ground motion to the ballast layer, thus causing some vibratory effects. The vibrations may not be visible, in other words, the ballast particle may not move. Still, the ballast particles lying on the top layer of the ballast crib could become sensitive to the input ground motions sparked by the minor earthquake. Earthquakes of magnitude 3 or less normally do not cause a slowdown of operations, since there is not enough energy released to cause any damage to the track structure itself. A second factor of risk related to the ground conditions can be found in the different response of the sub-ballast layer. A hot-mix asphalt layer presents a different dynamic response to that of an unbound aggregate or other stabilized material. Furthermore, one has to consider the areas of track transitions such as from an embankment to a viaduct/tunnel or a bridge approach. Transitions of the track substructure have an effect in terms of the differential settlement and change in the stiffness, thus a different type of response.

2.5. Atmospheric conditions

While it may not be considered relevant to the study of ballast particles in motion, atmospheric events might play a role in setting the right conditions for a particle to be picked up by a passing train. While several previous research studies discuss the effect of crosswinds on the body of the train, it is important to take into account the effect of those same crosswinds on the ballast structure (Baker, 2013, Sima & Venkatasalam, 2013) . High winds blowing on the track could alter the arrangement of the particles laying on the surface of the trackbed. This effect is particularly important with respect to smaller ballast particles present in the ballast for the reasons described previously.

High speed lines have been built under several operating environments. Extreme conditions can also cause foreign objects such as ice falling off the train to lead to ballast motions. The French Railroad

Agency SNCF has conducted some experimental modeling to simulate the falling of ice from a moving train. As the train travels in cold and freezing climates, ice can buildup in the covering region of the wheelset (Saussine G. , Allain, Vaillant, Ribourg, & Neel, 2013). When a train, for example, goes through a tunnel and experiences a temperature change, the ice may start melting, thus falling off the train.

2.6. Risk mitigation strategies

The phenomenon of flying ballast is still not well understood, in the sense that the initiating mechanisms are still not completely known. This section discusses potential risk mitigation strategies to reduce the likelihood of a ballast flight event.

The simplest mitigation strategy would be to reduce the speed of the trains. This solution, however, defeats the main purpose of high speed lines. In France and other countries where snow is a factor affecting performance of the high speed lines, there are provisions that include a temporary speed reduction in case of bad weather. For example, in France, SNCF has an agreement with the local weather service that allows the railroad to inform its customers on a three day notice that there will be delays in service due to bad weather (Saussine G. , Allain, Vaillant, Ribourg, & Neel, 2013)

Slab track is another mitigation strategy that would not only address the problem of flying ballast at high speeds, but would also bring other benefits in terms of life-cycle maintenance and performance over time of a HSR line. Despite these evident benefits, the cost of replacing ballasted track with slab track is most likely prohibitive. Slab track could be a solution to look into during the planning stages of a new high speed line.

Lowering the ballast profile by 2 or 3 cm (0.8 – 1.2 in.) is a risk mitigation strategy adopted by several countries, such as France, Italy and Spain. As discussed previously, the stones that are more prone to be picked up are the ones laying on the surface of the crib. By lowering the ballast profile voids are

Figure 2 - Ballast profile lowered on the Rome-Naples HSL (Agretti, 2012)

created between the bottom of the rail and the top of the ballast, as shown in Figure 2. Air that is compressed between the train and then track is now allowed to escape through these voids. The aerodynamic pressure is then reduced. This solution has appeared to have given good results in Italy and other countries. It is worth noting that in France this solution caused an increase in the tamping frequency. This could be explained by the fact that a lower ballast profile also implies a lower lateral resistance.

Ballast bagging is another risk mitigation strategy tested in Japan on those sections of the Shinkansen with ballasted track, as shown in Figure 3. The advantage of this solution is that the ballast particles are contained within the “bag”, thus no ballast flight can occur. All the other functions of ballast are retained (drainage, lateral stability, stress distribution). The disadvantage is that the

Figure 3 - Ballast Bag; the solution proposed in Japan (photo by T.C. Kao)

bags need to be removed and replaced for track maintenance.

In Spain, the railroad administrator, ADIF has developed a new type of sleeper under a project called Aurigidas (Alfonso, 2013). The sleepers have been installed on a small portion of the Madrid – Barcelona HSL, and it appears that the aerodynamic forces felt by the updated trackbed are about 21% lower compared to that of a “regular” trackbed. The solution is still under development.

3. Semi-quantitative risk analysis

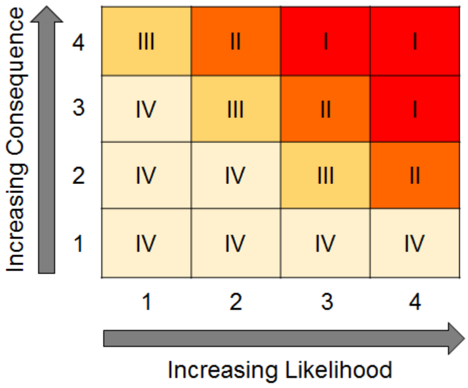

Figure 4 - Sample risk matrix model (CCPS, 2008)

Future work in this research will involve the development of a semi-quantitative risk analysis framework. To be able to assign a risk value to a pair of probability-consequence, one can use a risk matrix similar to the one shown in Figure 4. Based upon the literature and personal communication with railway experts who have dealt with flying ballast phenomenon in the field, it appears that the aerodynamic forces generated by a train travelling at high speeds are the main contributors to the initiating motion of the ballast particles. Therefore, as a quick example, one could say that the likelyhood of flying ballast based on aerodynamic forces should fall between 3 and 4 (likely to very likely) risk value. The consequences could then fall somewhere between 2 and 4 (minor damage to casualties).

Future work on this semi-quantitave risk analysis approach will include a method to determine the most accurate likelyhood of ballast flying based upon the risk categories presented in the previous sections. Likewise, a similar method will be developed to estimate the magnitude of the consequences of flying ballast.

4. Conclusions

This article presented a preliminary list of possible rick factors that may contribute to flying ballast. Some of the mitigating strategies adopted in countries where HSR is in operations have been presented. The future work for this project is to develop a semi-quantitative risk analysis method based upon the factors discussed in this paper.

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