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Investigating the impact of frost heave and thaw softening on changing the vertical force at wheel/rail interface

Alireza Roghani, Yan Liu, & Paul Burgess
National Research Council Canada, Ottawa, Ontario, Canada

ABSTRACT

The frost heave results in non-uniform deformation and irregularity on railway track. These irregularities increase the dynamic response of the train-track system, resulting in rapid deterioration of track geometry, and poor ride quality. Large surface roughness may cause unloading of wheels and consequently could lead to derailment. This paper presents the results of employing NUCARS® (New and Untried Car Analytic Regime Simulation) software to evaluate the interaction between rail car and the track as it passes through the frost bumps measured over a railway track section during two freeze-thaw monitoring seasons. The vertical wheel/rail forces (force exerted on the wheel by the rail) at each wheel resulting from the simulation is compared against Association of American Railroads (AAR) standard (Chapter 11 of the AAR Manual of Standards and Recommended Practices Section C - Part II) to determine how passing through the frost susceptible sections may affect the safety of train operations. According to AAR Specification M1001 Chapter XI track worthiness limits, the minimum vertical wheel load should be greater than 10% of the static condition. Using the measured track deformation at a study site located on VIA Rail subdivision in eastern Ontario, the minimum vertical force of 72% of the static load was observed as a result of using the track profile measured during thawing season. This value, which is well above the AAR's 10% requirement, occurred at the culvert location where there was large non-uniform deformation. Also, by comparing the results of minimum and maximum vertical force for track in various stages of freezing-thawing cycle, it was observed that the thawing stage is creating the worst combination of the forces.

1 INTRODUCTION

The frost heave results in non-uniform deformation and irregularity on railway track. These irregularities increase the dynamic response of the train-track system, resulting in rapid deterioration of track geometry, and poor ride quality (Cai, et.al, 2019).

To ensure safe passage of trains, railways strive to monitor track conditions during freezing-thawing seasons. During winter, the track inspection is mainly visual and relies on manual measurements while in spring test car is used to measure track geometry parameters over long distances.

According to Transport Canada's Rules Respecting Track Safety (Transport Canada, 2011), the track surface must be maintained to the class 5 level for passenger trains to run at 100 mph. For the class 5 track, the deviation from uniform surface on either rail at the centre of a 62-foot chord may not be more than 1.25 in (or 31.75 mm). Railways normally define a near-urgent defect which is approximately 90% of the TC's threshold values. In the case of the surface bump, the near-urgent limit is 1 in or 25.4 mm.

As measured in winter (Roghani 2021), track surface condition could change considerably in a relatively short period of time caused by freeze-thaw cycles (FTC). Thus changes could come and go without being recorded by track geometry car. This paper aims to evaluate potential safety concern due to the measured surface conditions. The study investigates the effect of track irregularities caused by FTC on the variation of vertical wheel/rail force. The track irregularities have been measured using total station surveys over a 50 m test section during two freeze-thaw seasons. These measurements are imported in a numerical model to estimate the vertical wheel/rail force. These forces are then compared against Association of American Railroads (AAR) standard (Chapter 11 of the AAR Manual of Standards and Recommended Practices Section C - Part II) to determine how passing through the frost susceptible sections may affect the safety of train operations. According to AAR Specification M1001 Chapter XI track worthiness limits, the minimum vertical wheel load should be greater than 10% of the static condition. The other AAR criteria are related to maximum ratio of vertical to lateral force which does not apply to the current study as the test section is located

on a tangent track and as a result has no lateral load generated.

1.1 Study site

A 50 m tangent section of track along one of VIA Rail's subdivisions in eastern Ontario has been used as the test site for this study (Roghani et al., 2019, Le Borgne et al., 2019). This section is only used for passenger trains and consists of 57 kg/m (115 lb/yd) continuously welded rail on ballasted track and wooden ties. Several frost/thaw issues have been reported in the past at this section with the most significant problem occurring towards the east end of the section where three culverts are located. The issues included large frost heave in winter and large dip in track profile during spring. According to track personnel, in some cases in the past they had to put a slow order at this site during winter to ensure the safe passage of the trains.

1.2 Total station survey

The absolute vertical deformation of the test site during the monitoring period was measured using total station. In total, 8 total station surveys were conducted at the test section with the baseline measurements were collected in June 2018. During 2018-2019 freeze–thaw season, the first survey was conducted in November when the track was not started freezing yet. The subsequent surveys of that season conducted in late January and late April when the track was in frozen and thawing conditions respectively. In 2019-2020 monitoring season, 4 surveys were conducted with the first one collected in early December (pre-freezing condition), second and third survey in late January and February (track in frozen condition), and the fourth survey in mid-March (track in thawing condition). Figure 1 presents the results of the total station survey with Figure 1a showing the measurements collected in winter-spring 2018-2019 and Figure 1b showing the results for winter-spring 2019-2020. From these figures, it is evident that the heave not only occurs non-uniformly over each side of the track, but there is also a difference between the deformations of the two sides at each location. The results also demonstrate that the largest heave occurs at the culvert location, with a maximum of 17 mm and 19 mm recorded in winter 2019 and 2020, respectively. On average, the track outside of the culvert zone heaved about 6.9 and 2.6 mm during winter 2019 and winter 2020, respectively (Roghani, 2021). It needs be noted that these numbers should not be compared against the Transport Canada threshold values for profile measurements as the measuring methods for the two datasets are different.

The lower frost heave during 2020 winter is consisted with its warmer ambient temperature, shorter freezing season, and less frost penetration depth compared to winter 2019 (Figure 2). In addition, during 2020 winter, track embankment at the test site experienced 4 intermittent FTC compared to 1 FTC observed during 2019 winter. According to the predictions by climate scientists, winter similar to 2020,

is expected to become the new normal. Table 1 compares the ambient and embankment temperature during the two winter-spring season.

Table 1. Comparing ambient and embankment temperature between two monitoring periods.

Sensor	2018-2019	2019-2020
Start of freezing season ¹	Jan 9, 2019	Jan 18, 2020
Start of thawing season	Mar 15, 2019	Feb 25, 2020
Maximum frost depth	1.0 m	0.5 m
Average temperature ²	-7.5 °C	-4.1 °C

¹ When the thermistor at 0.35 m below track surface recorded 0 °C.

² Average ambient temperature between December and March.

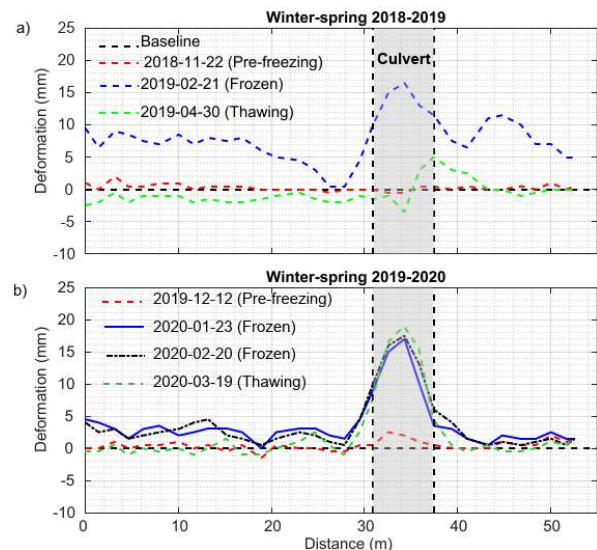


Figure 1. Plots showing track surface deformation during a) winter-spring 2018-2019 and b) 2019-2020 collected by total station surveys (after Roghani, 2021).

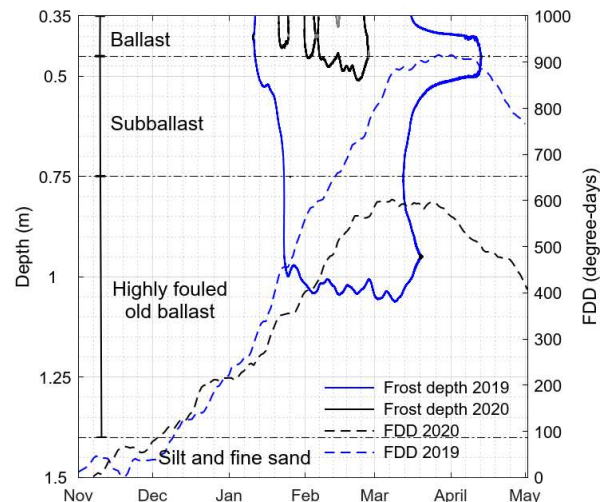


Figure 2. The variation of FDDs and the frost depth during winter 2019 and winter 2020 (after Roghani, 2021).

2 DEVELOPMENT OF NUMERICAL MODEL

This section presents the model developed in NUCARS® (New and Untried Car Analytic Regime Simulation) software to evaluate the interaction between rail car and the track as it passes through the frost bumps measured during each of 2019 and 2020 survey over the test site (Figure 1). NUCARS® is a software developed by Transportation Technology Center, Inc. (TTCI) for modelling rail vehicle transient and steady-state response. This software is an industry-accepted simulation tool used to examine the dynamic performance of rolling stock on track with varying types and levels of perturbation. The following sections discuss the input data into the simulation.

2.1 Rail car model

The rail car model used for this analysis was borrowed from a previous project based on the characteristics of the 4-axle passenger coach car currently used in VIA service. The coach car is modelled as a rigid H-frame bogie equipped with primary and secondary suspensions. The primary suspension is comprised of axle boxes that are connected to the bogie frame through axle box radius rods. There are two coil springs per axle box (four per axle). There are also two primary vertical hydraulic dampers per axle box (four per axle). The primary coil springs are modelled as springs with longitudinal, lateral, vertical, and rotational (roll) stiffness. The secondary suspension uses two air springs per bogie. Each air spring is simplified as a linear spring and a linear series spring-damper.

In the present simulation, the empty coach car with a “worn” suspension was used. The “worn” condition was simulated by reducing damping values by 20%. The gross rail load or the total weight of the simulated coach car is 109,250 lbs. This gives a static wheel load of 13,656 lb (13.7 kips).

2.2 Wheel/rail contact geometry

Since present simulations on the tangent track focuses on the vertical response due to frost heave, the wheel/rail contact details such as tread taper and flange contact angle will have little effect to results. Therefore, a wheel/rail contact file from NUCARS library was used in the simulation (A1b136104.wnt). The wheel back-to-back spacing was set at 53.375 in.

2.3 Track geometry input data

The track geometry parameters imported in this model include: Gauge, Alignment, Crosslevel, and Profile. Figure 3 shows the gauge and alignment data used as import data into the simulation. The gauge measurements shown in Figure 3a represent deviation from 56.5” standard gauge (positive means wider gauge) and Figure 3b represents deviation from a perfectly straight rail line. The profile and crosslevel were calculated using the survey measurements (Figure 1). It

should be mentioned that as there were no geometry measurements available for each survey, the gauge and alignment variations were assumed to be same for all the survey dates. This assumption is expected to have an insignificant effect on the main simulation results. This is because the gauge and alignment only have a very limited impact on vertical dynamics of vehicle track interaction. On the other hand, crosslevel and profile variations provide the main excitation to the vehicle’s vertical response.

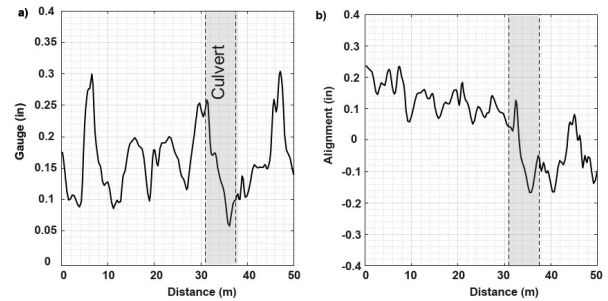


Figure 3. Plots show a) gauge and b) alignment variation over the test section imported in the NUCARS software.

3 RESULTS AND DISCUSSION

The simulation was conducted for each set of profile measurements collected during surveys (Figure 1) and repeated for speed ranging from 40–100 mph, in 20 mph increments. The speed range was selected to define the track resonance behaviour (if any). The variations of vertical force of each wheel on the passenger coach car were then extracted for each simulation. These results are presented in Figure 5, for surface deformations recorded in 2019, and Figure 6, for surface measurements recorded in 2020 (the relative location of axles and wheels are shown in Figure 4). Each plot shows the variation of the vertical force, the magnitude and location of minimum and maximum load, and the static load. It needs to be noted that vertical force for wheels of the first and second axles are presented in these plot. Similar plots were generated for axles 3 and 4.

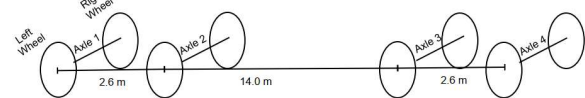


Figure 4. The location of axles and wheels used in simulation.

Figure 5 shows the variation of vertical force for each wheel as the train passes through the track profile measured during 2019 surveys. According to this plot, the minimum force is approximately 10.7 kips and occurs as a result of the track profile measured in 2019-04-30 (track in thawing condition). This value is about 79% of the static load and thus it is well within the safe limits. It is also evident that the minimum load is occurring within the proximity of the culverts. The maximum vertical load

of 17.2 kips also happens during 2019-04-30 survey measurements which is about 25% higher than the static load. Even though AAR does not specify any safety limits for maximum vertical load, the higher forces indicate higher stress on track components and rolling stock that may shorten their service life.

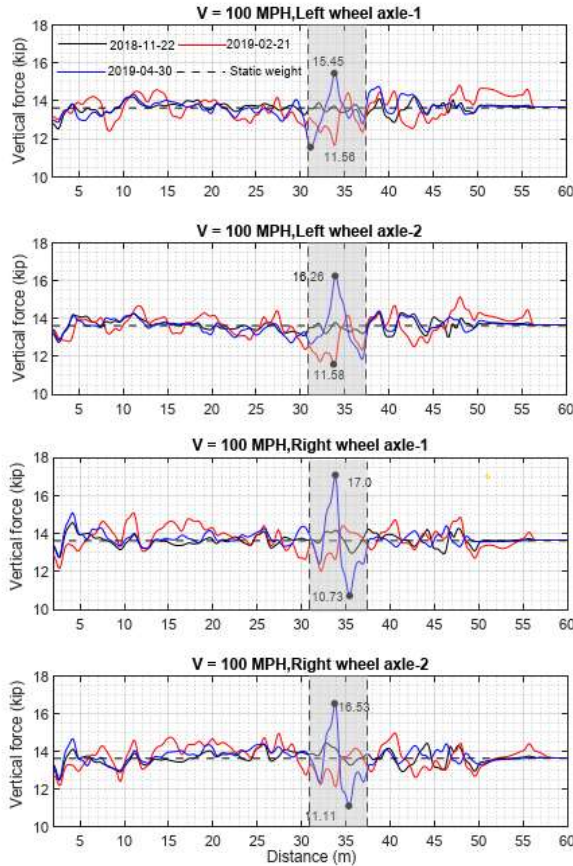


Figure 5. The variation of vertical force along the test section resulted from using 2019 survey measurements in NUCARS simulation. Note: The shaded area is the approximate location of the culverts.

Figure 6 compares the force variation as a result of 2020 profile measurements for a 100 mph operating speed. The minimum and maximum observed force is about 9.9 and 17.4 kips which is approximately equal to 72% and 128% of the static load, respectively. These values occur as a result of 2020-03-19 survey profile measurements in which the track is in a thawing stage.

Similar simulations were conducted for operating speed of 40, 60, and 80 mph and the results presented in

Table 2. Even though all the values are well within the AAR safety limit (greater than 10 percent of static load), they clearly show the effect of frost heave on changing the vertical force at wheel/rail interface. It should also be mentioned that for all these simulations, the worst condition occurred at the culvert location where the maximum frost heave was measured. No resonance effect was observed within the simulated speed range. The train speed plays an important role on the wheel unloading when passing the frost heaved zone. The

higher the speed, the higher the unloading risk. The effect of speed is more clearly demonstrated in Figure 7 where the change in the difference between maximum and minimum force at various operating speed is shown.

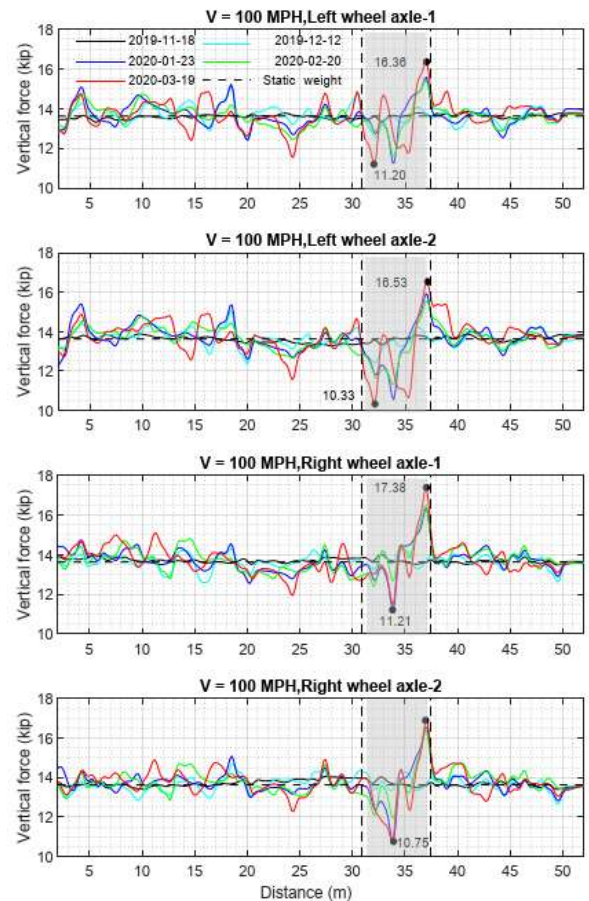


Figure 6. The variation of vertical force along the test section resulted from using 2020 survey measurements in NUCARS simulation.

Table 2. Summary of NUCARS simulation results (units in kips). Note: static vertical force is equal to 13.7 kips.

Track condition	Speed							
	40 mph		60 mph		80 mph		100 mph	
	Min VF	Max VF	Min VF	Max VF	Min VF	Max VF	Min VF	Max VF
2018-11-22 (Pre-freezing)	12.8	14.5	12.9	14.4	12.8	14.4	12.5	14.6
2019-02-21 (Frozen)	12.3	14.8	12.5	14.6	11.9	14.8	11.3	15.2
2019-04-30 (Thawed)	12.2	15.2	11.8	14.9	11.5	16.1	10.7	17.2
2019-12-12 (Pre-freezing)	12.9	14.2	12.9	14.5	12.5	14.8	12.2	15.2
2020-01-23 (Frozen)	12.2	14.9	12.0	15.3	11.2	15.9	10.3	16.6
2020-02-20 (Frozen)	12.0	14.8	12.1	15.23	11.8	15.9	11.2	16.5
2020-03-19 (Thawing)	12.12	15.5	11.4	15.8	10.7	16.5	9.9	17.4

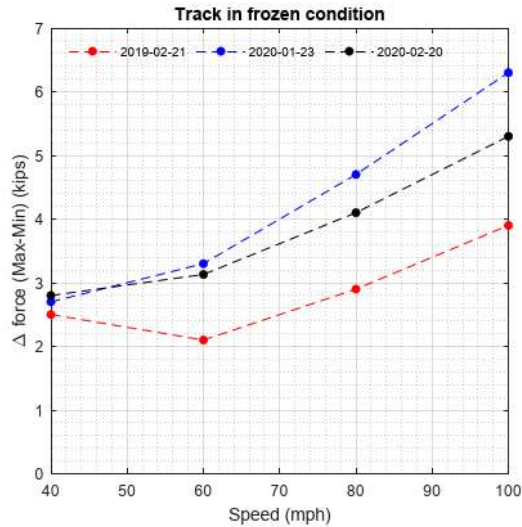


Figure 7. Plot compares the difference between maximum and minimum vertical force while track was in frozen condition.

Figure 8 compares the minimum and maximum vertical force for track in pre-freezing, frozen, thawing, and after thawing conditions. These results suggest that among the various states of track, the thawing stage is creating the worst combination of forces.

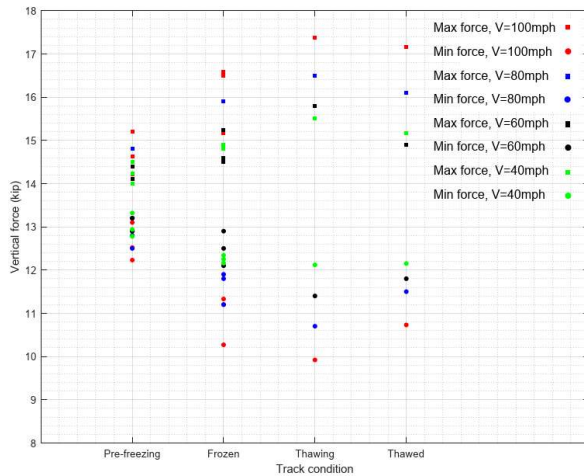


Figure 8. Plot shows the variation of minimum and maximum vertical force for various operating speed and track condition.

4 CONCLUSIONS

A numerical analysis was performed in NUCARS® software to quantify the effect of the non-uniform track deformation measured at the test site on the vertical force at the each wheel of a VIA's coach car. The simulation results were compared against the American Association of Railroad (AAR) specification that requires the minimum vertical load should be greater than 10 percent of static load (to prevent wheel unloading). The worst (minimum) vertical force of 72% of the static load was observed as a result of using the track profile

measured during 2020 thawing season. This value, which is well above the AAR's 10% requirement, occurred at the culvert location. Also, in comparing the results of minimum and maximum vertical force for track in freezing, frozen, thawing, and after thawing condition, it was observed that for these various states of track, the thawing stage is creating the worst combination of the forces.

Overall, the results indicated that 2020 winter created a worse (but still safe) operating condition than 2019. This can be attributed to larger differential deformation resulted from more FTC in winter 2020 and a stronger weakening effect caused by higher moisture content. The simulation results are also consistent with measurements from track geometry car which suggested that track was in poorer conditions in spring 2020 than spring 2019.

The limited numerical modelling conducted in this project suggested that even though the warmer and drier winter (similar to winter 2020) may result in a shorter freezing period and shallower frost depth, the higher number of intermittent FTC lead to larger differential frost heave in winter and higher vertical force at the wheel/rail contact point. This may lead to a condition that is more detrimental for track geometry and safe operations than a cold winter. According to the predictions by climate scientists, this type of winter, warmer and drier with frequent FTC, is expected to become the new normal and therefore, frequent maintenance may be required to keep railway tracks constructed in seasonally frozen ground within the safe limits. The failure to account for these changes may lead to the increased costs to infrastructure owners, unforeseen costs to infrastructure users, and considerable negative socioeconomic impacts. The research conducted in this project was limited in scope and was performed over a well-maintained class 5 track in Ontario. The performance of a lower-class track in a colder region of Canada may be different. In the authors' opinions, further research and development is required.

It also needs to be reminded that the results presented in this paper represent the VIA's coach car response to the limited observations measured at a very well maintained site during winter 2019 and 2020 and thus the results should not be generalized.

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