Chapter 5

Track Geometry Data Analysis

This chapter explains how and why the data collected for the track geometry was manipulated. The results of these studies in the time and frequency domain are addressed. The implications of the data with respect to track parameters and various degrees of curvature and subgrade stiffness are described. The initial data reduction methods are addressed, followed by conclusions on the nature of the data and a discussion of methods for further analyzing the data. The chapter concludes with the final analysis of the data and a discussion of "lessons learned" for implementation into future similar tests.

5.1 Initial Data Analysis

As with the wheel load data analysis described in Chapter 4, it was desired to know the nature of the complete loop track geometry data before focusing on specific areas. As explained in Chapter 3, the track geometry data was collected on the High Tonnage Loop at Transportation Technology Center Inc. (TTCI), as shown in Figure 3.1. The data has been collected at regular intervals similar to the intervals at which the wheel load data was collected, for accumulated traffic levels from approximately 100 Million Gross Tons (MGT) to over 600 MGT. The data was recorded on the track parameters described in Chapter 3 (i.e., left rail alignment, right rail alignment, gauge, crosslevel, left rail vertical profile, and right rail vertical profile) versus the distance traveled around the HTL.
As compared to the wheel load data described earlier, the track geometry data was collected in a significantly different manner. The data for the track parameters was collected at a sampling rate of one sample per foot. For a 40 mph vehicle speed, this spatial sampling frequency is equivalent to a 58.67 Hz sampling frequency in the time domain, approximately 8.7 times slower than wheel load data. Additionally, only information for the six track parameters and distance were contained in each file instead of the 16 separate measurements stored in the wheel load files. Together, these two facts resulted in data files that were about 20 times smaller, and much more manageable than the original wheel load data files. Therefore, it was not necessary to reduce the size of the track geometry data files. Since the maximum frequency that can be compared between the wheel load data and track geometry data was limited by the sampling frequency of the track measurements, it was not advantageous to eliminate any frequency contents from these measurements.

The analysis of the track data for the complete loop shows a significant amount of useful information. The vertical profile and gauge of the track have normal distributions, but as shown in Figure 5.1, the amplitude distributions for several of the track parameters are non-normal for the complete loop. In particular, the measurements for the left and right alignments display bimodal distributions. The histogram for the crosslevel shows a trimodal distribution. Examining spatial plots of the complete loop data for various parameters, such as the crosslevel data shown in Figure 5.2, shows the reasons for the non-normal distributions observed in the track data.
Various parameters have significantly different behaviors in different sections of the track, which are strongly dependent on the track curvature as depicted in Figure 5.2. During curves, the alignment and crosslevel are designed with non-zero values, while they have mean zero distributions during tangent sections. As shown in Figure 5.2, the spatial plot for the crosslevel agrees with this assessment of the situation. During the left-hand curves (sections 3 and 25), the crosslevel is significantly greater than zero. During the right-hand curve of section 7, the crosslevel is significantly below zero. This relationship creates a trimodal distribution with each concentration focused approximately at the value of crosslevel which occurs for the tangent, left, and right-hand curves. A similar situation occurs for the alignment, although the difference in the alignment resulting from the
single right-hand curve section is not significant enough to cause a third noticeable peak in the amplitude distribution.

![Spatial Plot of Crosslevel for HTL, 532 MGT](image)

**Figure 5.2. Crosslevel as a Function of Distance for the TTCI's High Tonnage Loop**

As with the wheel load data, the amplitude distribution for the track geometry data alludes to the different sections of data representing different populations. Accordingly, the track parameters were subdivided into the same five sections as the wheel load data, sections 3, 7, 25, 29, and 33. The separate sections may or may not induce the same dynamic frequencies into the rail vehicle. In order to determine the effect of each section on the frequency contents of the data, the overall power spectrum density (PSD) must first be established.

As shown in Figure 5.3, the track parameters for the complete loop primarily excite the vehicle at low frequencies (i.e., below 5 Hz). Most of the
track parameters contain very little content above 2 Hz. The profile for the right and left rail, however, has a generally higher frequency than the other parameters. It is worth noting that Figure 5.3 represents only one file and is intended as an example of the frequency contents evident in the complete HTL for a single measurement file. The power spectrum densities for different MGT levels exhibited different shapes, most likely caused by various factors that may have occurred during the long period that the data was collected, such as track maintenance, wear, and changes in the data collection systems. These differences will be addressed in a later section.

![Power Spectrum Density (PSD) for Track Geometry Corresponding to One Complete Loop on the HTL at 532 MGT of Accumulated Traffic](image)

The analysis of the complete loop data shows the significance of analyzing the data separately for various sections.
5.2 Sectional Frequency Analysis

The track geometry data was subdivided into five sections in the same manner as the wheel load data. These sections consisted of three curves of various degrees of curvature, and two tangent tracks with soft and firm subgrades. For comparison with the wheel load data, the track geometry data was divided into the sections corresponding to the NACO Wedgelock and Buckeye/Barber trucks. This chapter only addresses the information present in the track geometry data, as influenced by the subgrade and degree of curvature. Deviations of the track parameters with respect to the MGT level are addressed, but they are not related to the two trucks since the truck designs do not influence them.

As shown in Figure 5.4, the frequency contents for the track geometry parameters are significantly different for a curved section than for the complete loop. The higher frequency contents for the rail are less defined than the complete loop spectra. The principle locations of content are also different for the alignment. In this section, the alignment has more concentration of high frequency (> 0.5Hz) energy content than was presented in the complete loop analysis. As with the complete loop, these results varied with different MGT levels. This figure is simply intended to display the way in which the analysis of the different sections produces different results than the analysis for the complete loop data.
As shown in Figure 5.5, the PSDs for tangent sections are different than those for the complete loop or the curved sections. The PSDs for the profile show a higher concentration of high frequency contents as compared to the PSDs for section 25. The alignment shows more concentration for the low frequency contents. The frequency contents of the complete loop data is noticeably different than either of the two sections shown, however, the content present in each of the two individual sections can be seen in the frequency contents of the complete loop data.
Figure 5.5. Power Spectrum Density (PSD) for Track Geometry Corresponding to a Tangent Section with a Soft Subgrade

Overall, the sectional frequency analysis shows that each section of the HTL subjects the vehicle to a wide range of dynamic inputs. This analysis shows that the vehicle/track interaction needs to be analyzed separately for curved and tangent sections. As such, the five sections chosen for study will highlight the effect of track curvature and subgrade on the frequency contents of the track parameters. The variation of the track parameters from one data file to another is significant and must be addressed in detail before any conclusions can be drawn regarding the nature of frequency contents of the track data.
5.3 Sectional Amplitude Analysis

As shown in Figure 5.6, the amplitude distributions of the track parameters for each section have normal distributions. The mean values for the alignment and crosslevel distributions are non-zero for the 5 degree curve in section 3. The standard deviation of the profile and gauge seems to be lower for this section than the overall loop. Assuming that the distributions for these parameters have equal standard deviations along the loop, the standard deviation for any section of the loop would be lower than the whole loop. As is the case for every normally distributed population, an increase in the number of samples results in an increase in the sample population's standard deviation. To generalize these results, however, assumes that each section of the loop is consistently a sample of the same population for both the gauge and profile parameters. Since this assumption needs additional support, further analysis is conducted in later sections of this chapter.
As shown in Figure 5.7, the track parameters for tangent sections of track are also normally distributed. The mean values for the crosslevel and alignment are much closer to zero in this section than in curved sections, as is expected. The standard deviation for the vertical profile was also larger in this section than that for other sections of the track. From the individual data files, it was apparent that some relationship existed between the standard deviation of the track parameters and the properties of various sections.
The separate analysis of the different sections for each MGT level revealed significant findings in the amplitude distributions which needed further explanation. The majority of the distributions were normal when evaluated for individual sections. Although the spatial differences for various MGT levels were fewer than the differences among the PSDs for various MGT levels, the conclusions would still be more statistically viable for an aggregate of the data.

The exact nature of the relationships between the subgrade, degree of curvature and variation in track parameters can be more fully evaluated when the distribution for each of the sections is completely defined by one histogram instead of many. The differences existing between the amplitude distributions for each MGT level could be related to any of a number of conditions. The data for each MGT level has been divided into several
section for the purpose of evaluating the effect of the subgrade stiffness and
degree of curvature on the track parameters. The curvature and subgrade
are constant conditions within each section for all of the MGT levels
analyzed. As such, the variation of the distributions for different MGT levels
is not an aspect being studied, but the variation of the distributions for
different track conditions is. The distributions for the various MGT levels
were combined and compared as explained later in this chapter.

5.4 Aggregate Frequency Analysis

The aggregates of the Power Spectrum Density (PSD) were calculated
by averaging the PSDs for different MGT levels. This was intended to
determine which frequencies were common throughout the various MGTs.
The PSDs for each MGT level were calculated and then averaged with the
PSDs for the other MGT levels. The averaging process minimizes the effect
of frequencies not common to all of the MGT levels. Various methods for the
averaging process were attempted, but eventually a straight unweighted
average was selected as the method for combining the PSDs for the MGT
levels.

As shown in Figure 5.8, the gauge for various sections of the HTL has
a common low frequency content. The peak frequency for all of the sections
occurs at approximately 0.5 Hz and most of all the spectral energy occurs
below 2. As evident from Figure 5.8, the resolution of the frequency contents
has been significantly reduced. By reducing the number of spectral lines
used in each Fourier transform window, the PSD resolution has been
compromised. As a result, it is possible that signals with close frequencies
may be merged into one frequency band. The advantage of few spectral lines
is that a greater number of averages have taken place and a larger
percentage of the non-deterministic data has been removed. As such, the
peaks observed can accurately be addressed as common to the majority of the MGT levels.

![Aggregate PSD for Gauge, Various Sections](image)

**Figure 5.8. Aggregate Track Gauge PSD for Various Sections of the HTL**

Although the frequency results for gauge seemed largely independent of the section, the other track parameters showed a significant amount of variation from one section to another. As shown in Figure 5.9, the measurements for crosslevels revealed a second peak, above 2 Hz. The second peak occurs for both a curved section and a tangent section. The peaks occur at approximately 0.5 Hz and 2.3 Hz. Similar results were observed for the PSDs of the alignment measurements.
Figure 5.9. Aggregate Track Crosslevel PSD for Various Sections of the HTL

As shown in Figure 5.10, the PSD for the left alignment revealed a second peak for the curved section 25. This peak resembles the peak observed for crosslevel PSDs. The peaks for the alignment occur at slightly higher frequencies than either the crosslevel or the gauge peaks. These peaks occur at approximately 1 Hz and 2.75 Hz. The frequency analysis results for the right alignment, not shown for brevity, were similar to the left alignment, as is expected.
As shown in Figure 5.11, the frequency analysis for the left profile showed a single peak occurring between the first and second observed for the crosslevel and alignment PSDs. The PSD plots for the different sections are quite similar. Each section has a peak occurring at approximately 1.5 Hz. The existence of the track joints, as described in Chapter 4, may be the source of the peaks in the profile PSDs. The primary track joint input frequency occurs at 1.3 Hz for a forward speed of 40 mph and rail length of 39 ft. Once again, the PSDs of the right rail provided the same information as the left rail, and therefore, are not shown.
The aggregate frequency analysis shows the frequency ranges that are most prevalent in each parameter. Some of the track parameters displayed two distinct regions of spectral content. The primary regions for the gauge and crosslevel were at lower frequencies than the alignment or profile. The gauge and crosslevel displayed a primary peak around 0.5 Hz. The alignment parameters had primary peaks occurring at approximately 1 Hz, whereas the profile’s largest peaks occurred at around 1.5 Hz. The crosslevel and some of the alignment measurements displayed peaks at 2.3 Hz and 2.6 Hz, respectively. Overall, the frequency analysis of the track geometry provided useful information which may be used in the analysis of the track/wheel interaction. The data seemed accurate and corresponded well from one rail to the other, demonstrating repeatability.
5.5 Aggregate Amplitude Analysis

As shown in Figure 5.12, the aggregate data for the gauge measurements showed an approximately normal distribution. In order to provide a better statistical analysis of the amplitude distribution for various sections of the HTL, the data collected for different MGT levels were combined into an "aggregate" collection of data. Given the wide variety of conditions that existed for each MGT level over the ten years of data collection, the data seems extremely close to a normal distribution. In determining the amplitude distribution for each MGT level, it was found that the distributions for the gauge were normal in the majority of the cases studied. By averaging the amplitude distributions of the many data files, small irregularities from a specific data file not common to at least a few files would be minimized. Any major discrepancies in the means or standard deviations of the different population, however, would create a non-normal aggregate distribution. Although this situation did not arise for the gauge, some of the other track parameters did have non-normal aggregate distributions, even though the majority of the amplitude distributions or the individual files were normal.
As shown in Figure 5.13, the aggregate amplitude distributions for the crosslevel are normal for all sections except for section 7. Section 7 displays a slight bimodal distribution at the edge of the expected range of crosslevel for that region. The source of this distribution was not found, but is believed to be caused by an isolated case. Some of the files that were used in the analysis of the track geometry data did not correspond to files for the wheel load data and were therefore not analyzed as closely. One of these files is assumed to have a larger amount of interference than expected. The non-normality, however, was small and should not affect the later analysis. The figure also shows how each section affects the mean of the crosslevel. The crosslevel shows a negative mean of approximately 4 during a 5 degree right turn, a positive mean of approximately 5 during a 6 degree left turn, and a mean of approximately zero during tangent sections.
Figure 5.13. Aggregate Track Crosslevel Histograms for Various Sections of the HTL

Figure 5.14 shows a situation where the aggregate amplitude distributions were bimodal when the majority of the individual MGT levels displayed normally distributed distributions. The results for section 7 indicates two separate populations within the individual files for the left alignment. Analyzing the data further revealed that the mean value for the left alignment in this curved section had abruptly shifted by 0.7 inches at 512 MGT. The new mean was consistent from this traffic level until the end of the study. The nature of this shift in the mean is unclear. The results are too consistent to be interference, and one would not expect the track to wear in such an abrupt manner. Section 7 is a 5 degree right turn, whereas section 25 is a 6 degree left turn and should have roughly negative values of alignment from one another. As shown in Figure 5.14, the alignment for
section 25 does not display a bimodal distribution and is decisively positive. The results from the right alignment are more consistent and further draw into question the validity of the left alignment results for 512 MGT and higher.

![Aggregate Histograms for Left Alignment, Various Sections](image)

**Figure 5.14. Aggregate Left Alignment Histograms for Various Sections of the HTL**

As shown in Figure 5.15, the amplitude for the right alignment in each section is normally distributed. The right alignment should have approximately the same mean as the left alignment. Since the right alignment through section 7 has a mean of about -1 and is normally distributed, it seems reasonable to assume that the values obtained for the left alignment for 512 MGT and higher are offset in some non-intentional way. The amplitude distributions also reveal that the 6 degree curve has
approximately 1.5 inches of alignment and the tangent sections have an approximately zero mean, as may be expected.

![Aggregate Histograms for Right Alignment, Various Sections](image)

**Figure 5.15. Aggregate Right Alignment Histograms for Various Sections of the HTL**

The amplitude distribution shown in Figure 5.16 shows that the left vertical profile data is normally distributed with a mean of approximately zero. This data seems consistent from one rail to the other, and for the left- and right-hand curves. Overall, the distributions for the left profile were as expected from the analysis conducted on the data for the individual MGT levels.
As shown in Figure 5.17, the histograms for the right profile are bimodal with one mode occurring roughly at zero. Since the profile of the left and right rails should be similar, these are particularly interesting distributions. The distributions for the right profile for each of the data files were approximately normal. Similar to the left alignment, the data from 512 MGT and beyond displayed a mean of approximately 0.6 inches higher than the mean of the previous data. Without further information, it is not possible to determine the root cause of this shift in the data. To have a vertical profile on one rail higher than the other on tangent track does not conform to the standard practices.
Figure 5.17. Aggregate Right Profile Histograms for Various Sections of the HTL

Displaying the amplitude distributions for the track parameters in terms of aggregates has allowed several peculiarities to be detected that may have otherwise been overlooked. The data collection techniques for 512 MGT and beyond seem to have unrealistic values for the left alignment and right profile. The discrepancies in the data have made it necessary to perform the statistical analysis of the data in a specific format.
5.6 Effect of Accumulated Traffic on Track Parameters

The original concept for determining the aggregate response of the data was to find a single distribution that represented every data file. With this distribution, it would have been possible to make general statements about the effects of curvature and subgrade on the six track parameters. The data, however, has generated some unexpected results. There appears to be a biasing error in some of the measurements. This deviation makes it difficult to establish a meaningful representation by analyzing the aggregate distributions. Therefore, another method must be used for the statistical evaluation of the data.

There was little hope of removing the biasing error from the data without corrupting the integrity of the information. The deviation in the data appeared to only bias the data, as stated. Therefore, we decided to calculate the standard deviation of the population by averaging the standard deviation of each individual distribution, as opposed to calculating the standard deviation of the aggregate distributions.

Before averaging the standard deviations of the individual MGT levels, we decided to determine the nature of the standard deviations. Figure 5.18 shows the standard deviation of the alignment for the outside rail during the three curved sections for all MGT levels available. Sections 3 and 7, which are both 5 degree curves, experienced similar standard deviations. The standard deviation in the 6 degree curve, however, did not seem to correspond quite as well to the other two sections. This track parameter did not seem to experience a large amount of change throughout the MGT levels collected for this study.
As shown in Figure 5.19, the subgrade stiffness has no apparent effect on the variation of the alignment. The variation experienced from one rail to the other is significantly larger than the variation experienced between the two subgrade stiffnesses. Although the variation of the alignment is plotted for all MGT levels available, the subgrade stiffness in section 29 was not softened until approximately 223 MGT. Displaying all of the available data shows that no major transition occurred for the alignment when the subgrade was softened.
Variation of Left and Right Rail Alignments for Tangent Sections

Figure 5.19. Variations in the Alignment of Each Rail for Tangent Sections of the High Tonnage Loop (HTL) at TTCI

The results for the profile were similar to those for the alignment. As shown in Figure 5.20, the degree of curvature did not cause a significant change in the profile of the outer rail. The change in the standard deviation for this parameter for increasing MGT levels seemed quite uniform from one section to another.
As shown in Figure 5.21, the rail profiles in tangent sections are more varied than in the curved sections. There are no clear biases. The variations from one rail to another are greater than the variations between the soft and firm subgrades. Of the track parameters measured, the profile was the parameter most expected to have a dependence on the subgrade stiffness. Although the measurements for the profile did not exhibit any changes in the standard deviation of the profile, it is important to remember that the track measurement vehicle did not exert the same dynamic loading on the track as a typical rail vehicle. It is, therefore, still possible that the subgrade stiffness could affect the profile of the track that the rail vehicle actually travels along.
Variation of Left and Right Rail Profiles for Tangent Sections with Soft (Sec 29) and Firm (Sec 33) Subgrade Stiffness

Figure 5.21. Variations in the Profile of Each Rail for Tangent Sections of the High Tonnage Loop (HTL) at TTCI

As shown in Figure 5.22, the standard deviation (STD) of the gauge of the track seemed unaffected by the degree of curvature. There seemed to be little correlation between the gauge variance and the MGT level. For different MGT levels, the gauge's STD fluctuates irregularly for various sections. The STDs, however, appear to improve at approximately 380 MGT. Although the exact cause for this improvement is unknown, one may tend to believe that some form of track maintenance may be the source, as many of the other track parameters seem to also improve for this same point in time.
Figure 5.22. Variations in the Track Gauge for Curved Sections of the High Tonnage Loop (HTL) at TTCI

As shown in Figure 5.23, the standard deviation (STD) of the gauge seems to be affected by the subgrade stiffness. In the majority of cases studied after the softening of the subgrade at approximately 223 MGT, the standard deviation for the tangent section of track with a stiffer subgrade was greater than the standard deviation of the gauge for the section with a softer subgrade. The variation of the gauges before the subgrade was softened were very similar. There is a significant difference in the variation after the track modification.
Figure 5.23. Variations in the Track Gauge for Tangent Sections of the High Tonnage Loop (HTL) at TTCI

As shown in Figure 5.24, the standard deviation (STD) of the crosslevel does seem affected by the degree of curvature. The measurements for the 6 degree curve in section 25 have consistently greater standard deviations than the measurements for either of the 5 degree curves. Additionally, the general shape and trend of each curve agrees fairly well with the other curves. There is not much change from one measurement to another.
Figure 5.24. Variations in the Track Crosslevel for Curved Sections of the High Tonnage Loop (HTL) at TTCI

As shown in Figure 5.25, the standard deviation (STD) of the crosslevel appears to be affected by the subgrade stiffness. There is a large difference between the standard deviation of section 29 before and after the subgrade was softened. The STD of the measurements is significantly greater for files after 223 MGT. Further, the STD is significantly greater for the section with the softer subgrade than it is for the section with the firm subgrade.
As shown in Figure 5.26, the average standard deviations of the track parameters are relatively consistent for different degrees of curvature and subgrade stiffness except for the crosslevel. The STD of the crosslevel increases with the degree of curvature. The average crosslevel STD for all of the data files increased significantly from the 5 degree curves in sections 3 and 7 to the 6 degree curve in section 25.

The subgrade stiffness only seemed to produce noticeable effects in the gauge and crosslevel. An increase in the stiffness actually caused the STD of the gauge to increase, but caused the STD of the crosslevel to decrease. In general, the softer subgrade results in a 95% increase in the STD of the crosslevel, and a 29% decrease in the STD of the gauge.
5.7 Concluding Remarks

The analysis of the track parameters shows that it is difficult to read any conclusions from the data for the complete HTL loop. What appears to be a biasing error for some of the MGT levels prevents the formation of data with sufficient validity to be used in the determination of the track/wheel relationships. The analysis of the individual MGT levels revealed that the majority of the amplitude distributions were normally distributed. Therefore, the statistical properties of each MGT level were used to make comparisons of the effects of the degree of curvature and subgrade stiffness on track geometry variations.

As revealed earlier, the alignment and profile parameters did not seem to be significantly affected by subgrade stiffness or track curvature. The gauge and crosslevel standard deviations were found to be determinant on the subgrade stiffness. The gauge standard deviation decreased with a softer
subgrade, whereas the crosslevel standard deviation increased. The standard deviation of the crosslevel was also found to increase with the degree of curvature.

The data collection presented two major obstacles for the analysis of the track geometry data. First, the data was collected using a spatial frequency, whereas the wheel load data was collected using a time domain frequency. In order to relate the results from the two sets of data, a conversion factor is needed to bridge the gap between the spatial and time domain data. In this case, a constant 40 mph vehicle speed was assumed and used to convert all of the track geometry data into the time domain. Although it appears more logical to discuss track irregularities in the spatial domain, the results for this study were more easily interpreted in the time domain. The assumption of a constant 40 mph speed is obviously not ideal and another method should be used for this analysis. Additionally, the measurements for the track geometry were not taken under typical dynamic loading. This can distort the relationships that are observed between the wheel loads and rail parameters.

Overall, the track geometry measurements were analyzed successfully. The frequency bands that could be related to track inputs have been identified. The track parameters that were affected by the subgrade stiffness and degree of curvature were identified, and the relationships between these parameters were explored. The manner in which the track parameters have changed with increasing MGT levels was studied. Discrepancies between the MGT levels were identified and their root causes were estimated.