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Impact of Curvature on Track Geometry Safety Standards

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Impact of Curvature on Track Geometry Safety Standards

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16. Abstract

Based on about 269 miles of field test data, this investigation aimed to initially determine whether the current track geometry standards defining urgent defects for a given class of track should be further defined as a function of degree of track curvature.

Field test data for an empty tank car were organized into a comprehensive database and then analyzed in detail. The number of geometry defects, which occurred on track sections as tangent, spirals, and curves, was first compared with the instrumented wheelset force defects defined by AAR Chapter 11 wheel force ratio criteria. The quantitative relations relating track geometry, track curvature and wheel force ratio were then studied based on test data. It was found that (1) the threshold values of the studied track standards are generally more restrictive than that of the wheel force criteria of AAR Chapter 11 for the empty tank car; and (2) the threshold values of Warp31 and Twist62 on spiral/curve track with higher degrees of curvature should be more restrictive, while the threshold values on tangent track or spiral/curve track with lower degrees of curvature could be less restrictive for an empty tank car.

Two equations that quantitatively relate the force defects with track geometry defects and track curvatures were suggested from the present investigation. In order to apply these equations to develop a set of recommended values for track limiting value geometry defects that are defined as a function of degree of track curvature, it is recommended that further investigation on these equations, with considerations of the effect of different car types beyond an empty tank car and of the combination effects of different track defects, be conducted first by means of NUCARS simulations and then by field tests.

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16. Résumé

La présente étude repose sur des essais en vraie grandeur équivalant à un parcours d'environ 269 milles; elle visait initialement à déterminer s'il y a lieu d'incorporer le degré de courbure dans les normes actuelles visant la géométrie de la voie et définissant les défauts considérés graves pour une catégorie de voie.

Les données d'essais en vraie grandeur d'un wagon-citerne vide ont été colligées dans une base de données exhaustive, puis analysées en détail. Le nombre de défauts de géométrie détectés sur trois types de tracés, voies droites, voies courbes et courbes de raccordement, a d'abord été comparé avec les défauts générateurs de force à la roue, mesurés par un essieu instrumenté, et définis par le chapitre 11 du Manual of Standards and Recommended Practices de l'Association of American Railroads (AAR) comme le ratio des forces au point contact roue-rail. Les rapports quantitatifs reliés à la géométrie et à la courbure de la voie, et le ratio des forces au contact roue-rail ont été ensuite étudiés en regard des données résultant des essais. L'étude a permis de constater (1) que les valeurs seuils des normes examinées sont généralement plus restrictives que le critère défini au chapitre 11 du Manuel de l'AAR dans le cas d'un wagon-citerne vide et (2) que les valeurs seuils des défauts désignés Warp31 et Twist62 relevés sur des voies courbes et sur des courbes de raccordement à grand degré de courbure devraient être plus restrictives, tandis que les seuils pour voies à faible degré de courbure pourraient être moins restrictives pour un wagon-citerne vide.

La présente étude propose deux équations mettant en relation d'une part les défauts générateurs de forces et, d'autre part, les défauts de géométrie et la courbure de la voie. Avant d'utiliser ces deux équations pour établir des défauts limites de géométrie selon le degré de courbure de la voie, une étude plus approfondie s'impose, qui tiendra compte du type de wagon, chargé ou non, et de l'effet combiné de différents défauts de voie. La recherche procédera d'abord par des simulations NURAS, que des essais en vraie grandeur viendront compléter.

17. Mots clés: Règlement sur la sécurité de la voie, défaut de géométrie de la voie, courbure de la voie, essai en vraie grandeur, essieux instrumentés, ratio des forces L/V, critère du chapitre 11 de l'AAR		18. Diffusion: Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.		
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EXECUTIVE SUMMARY

Background

Currently, the Transport Canada *Rules Respecting Track Safety* recognizes only three types of alignment, namely tangent, spiral, and curves, without enough recognition of the degree of curvature. In several discussions among National Research Council Canada's Centre for Surface Transportation Technology (NRC - CSTT), railway regulators, BC Rail and other railway operators, it seems plausible that the degree of track curvature should be considered. It would have an influence on the magnitude of geometry defects necessary (in tangents, curves and spirals) to cause the empty car wheel-rail response forces to approach a value sufficient to bring an empty tank car to a high level risk of derailment. This investigation aimed to determine whether the current track geometry standards defining urgent defects for a given class of track should be further defined as a function of degree of track curvature.

Approach

BC Rail and NRC - CSTT initiated this investigation by collecting a large amount of field data in a test train during southbound testing between Prince George and Lilloet in April 1997. This test involved the simultaneous recording of track geometries using Canadian National Railway's (CN) Track Geometry Car, and tank car wheel-rail forces using the NRC - CSTT instrumented wheelsets installed on an empty tank car.

About 269 miles of field test data for the empty tank car were organized into a comprehensive database and then analyzed in detail. The number of geometry defects, which occurred on track sections with different track alignments, tangent, spirals, and curves, was first compared with the instrumented wheelset force defects defined by AAR Chapter 11 wheel force ratio criteria. The quantitative relations relating track geometry, track curvature and wheel force ratio were then studied based on test data. While not required in the scope of work, a few NUCARS (**N**ew and **U**ntried **C**ar **A**nalysis **R**egime **S**imulation, an AAR-approved software package for conducting dynamic simulation of a rail car) computer simulations of the empty tank car passing over track geometry defects were also performed to help the investigation.

Results and Conclusions

The following results and conclusions were obtained:

(1) The overall occurrence rate of geometry defects defined by Transport Canada's track standard or BC Rail's urgent standard is about six times higher than that of force defect defined by AAR Chapter 11 criteria, or 80% of the AAR criteria. This indicates that:

> **The threshold values of the studied track standards are generally more restrictive than that of the wheel force criteria of AAR Chapter 11 for the empty tank car.**

(2) For the same number of Twist62 defects, the occurrence of instrumented wheel force defect events on curve track is more than two times larger than that on tangent track. For the same number of Warp31 defects on spirals, the occurrence of instrumented wheelset force defect events increases as the degree of curve increases. These results, together with other observations of the present investigation, suggest the following argument:

The threshold values of Warp31 and Twist62 on spiral/curve track with higher degrees of curvature should be more restrictive, while the threshold values on tangent track or spiral/curve track with lower degrees of curvature could be less restrictive for an empty tank car.

(3) An equation that relates the Retained Vertical Load to Warp31 and Cant Deficiency on spirals was developed and partially confirmed from the present analysis of the field test data. Another equation to relate Wheel L/V Ratio to Track Alignment was suggested, based on the test result correlation between steady wheel L/V ratio and curve degree, and on the NUCARS simulation result on the relation between Wheel L/V Ratio and Alignment.

These equations, with further test or simulation confirmation and possible refinement, could be used as tools to quantitatively evaluate the effects of track curvature on the threshold values of track geometry defects in any future study of revision of track geometry standards. The data and analysis to date has been limited to an empty tank car.

Recommendation for Future Research

Preliminary results indicate that the investigation of the importance of track curvature on the Track Safety Standard, by an approach relating limiting values of track geometry parameters to car derailment force parameters, is a promising research direction for railway safety. Therefore, further research in this direction is strongly recommended. Some future work to be done could include:

(a) Further investigation into the relations between track alignment defects and wheel force defects like L/V ratio.
(b) Investigation into the effect of different car types other than an empty tank car.
(c) Investigation into the combination effects of different track defects.
(d) Establishment of reliable quantitative relations between limiting values of track geometry parameters, track curvature and wheel force ratios.
(e) Study of a set of recommended values for track limiting value geometry defects that are defined as a function of degree of track curvature and track class.

For the above items, a detailed investigation by NUCARS is strongly suggested before proceeding with further field tests. This is recommended based on the following features and advantages of the NUCARS simulation approach:

- It is easy to isolate the effect of each surface geometrical parameter on the force ratio.
- Different car types can be simulated and compared on the same track conditions.

- Different car and lading types will react quite differently to the various types of limiting track geometry errors and speed (class of track) of operation.
- Combination effects of different track defects can be quickly designed, simulated and evaluated.
- Track and operation conditions like defect amplitudes, track curvature and car speed can be systematically changed.
- Field data of track surface variations from BC Rail main line tests or other available field tests can be included into the simulation if necessary.
- Cost efficiency.

SOMMAIRE

Contexte

Actuellement, le *Règlement sur la sécurité de la voie* de Transports Canada ne reconnaît que trois types de tracés, soit les voies droites, les voies courbes et les courbes de raccordement. Le Règlement n'accorde pas suffisamment d'importance au degré de courbure. Suite à plusieurs discussions entre le Centre de technologie des transports de surface du Conseil national de recherches du Canada (CTTS-CNRC), les régulateurs en transport ferroviaire, BC Rail et d'autres opérateurs ferroviaires, il semble plausible de prendre en compte le degré de courbure de la voie. Ce paramètre accentuerait l'incidence des défauts de géométrie (en voies droites, en voies courbes et en courbes de raccordement) sur les forces de réaction requises pour qu'un wagon-citerne vide présente un risque élevé de déraillement. La présente étude consiste à déterminer si les normes actuelles définissant les défauts considérés graves pour une catégorie de voie devraient être réaménagées en fonction du degré de courbure.

Approche

Pour commencer, BC Rail ainsi que le CTTS-CNRC ont collecté une grande quantité de données lors d'essais menés en avril 1997 sur un convoi circulant de Prince George à Lilloet, soit en direction sud. La géométrie de la voie était enregistrée en temps réel par une voiture d'auscultation de la voie appartenant au CN; les forces au point de contact roue-rail dans le cas d'un wagon-citerne vide étaient mesurées sur des essieux instrumentés du CTTS-CNRC.

Le wagon-citerne vide a été soumis à des essais en vraie grandeur pour une distance totale d'environ 269 milles. Les données recueillies ont été colligées dans une base de données exhaustive, puis analysées en détail. Le nombre de défauts de géométrie détectés sur voies droites, voies courbes et courbes de raccordement a été comparé d'abord avec les défauts générateurs de forces, mesurés par un essieu instrumenté, et définis par le critère du ratio de forces à la roue mentionné au chapitre 11 du Manual of Standards and Recommended Practices de l'ARR. Les rapports quantitatifs entre la géométrie de la voie, la courbure de la voie et le ratio de forces au contact roue-rail ont ensuite été étudiés en prenant comme référence les données recueillies au cours des essais. De plus, bien que non requises par le projet, des simulations par ordinateur ont été réalisées pour faciliter l'investigation, à l'aide du logiciel NUCARS (**N**ew and **U**ntried **C**ar **A**nalysis **R**egime **S**imulation). Ce logiciel est approuvé par l'AAR pour reproduire la dynamique d'un véhicule ferroviaire. Il a servi en l'occurrence à simuler le passage de wagons-citernes vides sur une voie présentant des défauts de géométrie.

Résultats et conclusions

L'étude a donné les résultats et les conclusions ci-après :

(1) Le taux global d'occurrence de défauts de géométrie de la voie, selon les normes de Transports Canada sur la voie ferrée ou selon les normes de BC Rail sur les défauts graves, est environ six fois plus élevé que le taux de défauts générateurs de forces défini par le chapitre 11 de l'AAR, ou l'équivalent de 80 p. cent du critère de l'AAR. Cela indique que :

> **Les valeurs seuils des normes étudiées sont généralement plus restrictives que celles du critère de forces à la roue du chapitre 11 du Manuel de l'AAR dans le cas d'un wagon-citerne vide.**

(2) À nombre égal d'écarts de nivellement transversal (défauts désignés Twist62), l'occurrence des défauts générateurs de forces sur une voie en courbe est plus de deux fois supérieure à celle observée pour une voie droite. À nombre égal de variations de dénivellement transversal (défauts désignés Warp31) dans les courbes, l'occurrence des défauts de voie générateurs de forces à la roue mesurables par un essieu instrumenté augmente avec le degré de courbure. Les résultats et les observations de la présente investigation permettent d'avancer ce qui suit :

> **Les valeurs seuils des défauts Warp31 et Twist62 des courbes de raccordement/courbes à grand degré devraient être plus restrictives, alors que les valeurs seuils des droites, des courbes de raccordement ou des courbes à faible degré pourraient être moins restrictives pour les wagons-citernes vides.**

(3) Une équation mettant la charge verticale retenue en relation avec les défauts Warp31 et les défauts de dévers sur les raccordements a été développée, puis confirmée partiellement après la présente analyse des données des essais en vraie grandeur. Une autre équation, mettant en relation le ratio des forces L/V (forces latérales et forces verticales) à la roue avec le tracé de la voie a été proposée, fondée sur la corrélation entre le ratio L/V constant et le degré de la courbe, découlant des résultats des essais, et selon le résultat de la simulation NUCARS sur la relation entre le ratio L/V et le tracé de la voie.

> **Ces équations, si elles sont confirmées par d'autres essais ou des simulations, et si elles sont éventuellement perfectionnées, pourraient produire une évaluation quantitative des effets de la courbure de la voie sur les valeurs seuils des défauts de géométrie dans une future étude ou révision des normes pertinentes. Jusqu'à maintenant, les données et l'analyse concernaient un wagon-citerne vide.**

Recommandations pour la recherche future

Les résultats préliminaires donnent à penser qu'étudier les effets de la courbure de la voie sur les normes de sécurité, au moyen de la relation entre les valeurs limites des paramètres géométriques et les forces de déraillement d'un wagon constitue une approche porteuse de promesses pour la sécurité ferroviaire. Il est par conséquent fortement recommandé de poursuivre la recherche dans cette direction. Les perspectives de travaux sont susceptibles de porter entre autres sur les éléments suivants :

(a) Étude des relations entre les défauts de la voie et les défauts générateurs de forces, et plus particulièrement le ratio L/V.
(b) Étude de l'effet des wagons autres que les wagons-citernes vides.
(c) Étude des effets combinés de différents défauts de voie.
(d) Établissement de rapports quantitatifs fiables entre les limites des paramètres géométriques de la voie, la courbure de la voie et les ratios des forces à la roue.
(e) Étude de défauts limites de géométrie définis suivant le degré de courbure et la catégorie de la voie.

Pour ce qui est des éléments ci-dessus, il est fortement recommandé de procéder à une investigation détaillée par simulation NUCARS avant de poursuivre les essais en vraie grandeur. Cette recommandation est fondée sur les caractéristiques et les avantages ci-après de la technique de simulation NUCARS :

- Facilité d'isolement de l'influence de chaque paramètre de la géométrie de la voie sur le ratio des forces.
- Comparaison, au moyen de la simulation, de différents types de wagons en conditions de voie identiques.
- Réactions très variées de différents types de wagons et de chargements aux défauts de géométrie de la voie et à la vitesse des trains (selon la catégorie de voie).
- Rapidité d'établissement et de simulation des combinaisons de défauts de voie, et d'évaluation des effets.
- Les conditions de voie et d'exploitation, par exemple l'amplitude des défauts, la courbure de la voie et la vitesse de déplacement du wagon peuvent être systématiquement modifiées.
- Intégration à la simulation, au besoin, des données en vraie grandeur sur les variations de surface de la voie issues des essais menés par BC Rail sur ligne principale ou des résultats de tout autre essai en situation réelle.
- Outil présentant un rapport coût-efficacité intéressant.

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1. INTRODUCTION

Currently, the Transport Canada *Rules Respecting Track Safety* recognizes only three types of alignment, namely tangent, spiral, and curves, without enough recognition of the degree of curvature. In several discussions among National Research Council Canada's Centre for Surface Transportation Technology (NRC-CSTT), railway regulators, BC Rail and other railway operators, it seems plausible that the degree of track curvature should be considered. In particular for a empty tank car, It would have an influence on the magnitude of geometry defects necessary (in tangents, curves and spirals), to cause the car wheel-rail response forces to approach a value sufficient to bring the tank car to a high level risk of derailment.

BC Rail and NRC-CSTT initiated this investigation by collecting a large amount of field data in a test train during southbound testing between Prince George and Lilloet in April 1997. This test involved the simultaneous recording of track geometries using Canadian National Railway's (CN) Track Geometry Car, and tank car wheel-rail forces, using the NRC-CSTT instrumented wheelsets installed on an empty tank car.

This work was funded jointly by Transport Canada's Rail Safety Directorate, the Transportation Development Centre and BC Rail. Based on the available field data, this project aims to initially determine whether the current track geometry standards defining urgent defects for a given class of track should be further defined as a function of degree of track curvature.

About 269 miles of field test data for the empty tank car were organized into a comprehensive database and then analyzed in detail. The number of geometry defects, which occurred on track sections with different track alignments, tangent, spirals, and curves, was first compared with the instrumented wheelset force defects defined by AAR Chapter 11 wheel force ratio criteria. The quantitative relations relating track geometry, track curvature and wheel force ratio were then studied based on test data. A few NUCARS (New and Untried Car Analytic Regime Simulation) computer simulations of the empty tank car passing over track geometry defects were also performed to help the investigation.

2. FIELD TEST

2.1. General Description

The field tests were conducted by BC Rail and NRC-CSTT, assisted by CN and CANAC. The tests were carried out on BC Rail's main line track southbound from Prince George to Lillooet (MP463 to MP158), as shown in Figure 1, on April 30, 1997.

In addition to a routine defect scan of BC Rail track by CN's geometry car consist, an empty tank car equipped with NRC-CSTT's two instrumented wheelsets (IWS) was hooked to the test train to measure the wheel-rail forces at the same time. Figure 2 shows the test train consist, together with the locations where the major geometry and force parameter are measured. Both the track geometry channels and IWS force channels were recorded in NRC-CSTT's data acquisition system simultaneously during the whole test, for about 300 miles of track. Table 1 gives the major dimensions of the cars of the test train consist.

2.2. Geometry Car Measurements

The geometry cars employed in the tests were from CN and consist of the geometry coach and the instrumented box car shown in Figure 2. Available raw data of track geometry parameters recorded separately by NRC-CSTT from the geometry car include

- Left/Right Rail Vertical Profiles
- Gauge
- Track Curvature
- Superelevation

The Rail Vertical Profiles were measured with respect to inertial reference through appropriate band pass filtering and scaling of linear combinations of vertical accelerations on the trailing axle of the box car's leading truck. The Track Curvature was from the truck rotation angle measurements of both leading and trailing trucks of the coach car, and therefore located at the centre of the coach car. Superelevation was obtained by inertial measurement of the coach car floor angle combined with the relative angular deflection of the leading axle of the trailing truck.

All of the available geometry parameters were recorded in NRC-CSTT's data acquisition system by connecting to the geometry car's measurement system. The train speed was also recorded during the test, the signal of which was provided from the Track Geometry Car's speedometer/odometer system.

Unfortunately, no track Horizontal Alignment measurements were available in this test. The impact of not having track Horizontal Alignment data in this investigation is discussed in subsections 4.5 and 5.3.

2.3. Empty Tank Car and Instrumented Wheelsets

NRC-CSTT's instrumented wheelsets were installed on an empty tank car supplied by BC Rail for the rail-wheel force measurement. The tank car and the associated instrument caboose were hooked to the test train as shown in Figure 2. BC Rail personnel selected the tank car UTLX 29856 for this test because it was considered to be among the car types operating on BC Rail that had a historically high derailment potential. The tank car was tested under normal in-service conditions with all truck components within specified standards. Pertinent details of the tank car are as listed below:

LTWT = 100,100 lb. (this is the test condition, while LDLMT = 162,900 lb.)
Truck spacing = 53 ft.
Barber S-2 truck with D-5 suspension
Spring nest: 7 main outer, 6 main inner springs, double side coils
36 in. diameter wheels
Solid side bearers

Two NRC-CSTT Instrumented Wheelsets (IWS01 and IWS02) were installed on each truck of the tank car. IWS02 was installed on the leading truck, while IWS01 was installed on the trailing truck. They were both installed in the leading axle position of each truck, as shown in Figure 2.

The IWS's are able to measure the vertical rail-wheel force to 286,000 lb. car weight with about 5% uncertainty. They had virtually new AAR1B Wide Flange profiles, and were of equal 36 in. diameters during the test in 1997. An instrumented wheelset computer was used to control the operation of the IWS and to generate the measured data. The vertical, lateral and longitudinal dynamic forces, and contact points on wheels can be recorded continuously. Therefore, recorded on a common time base with the track geometry parameters, the following leading axle wheel force parameters are available for the present investigation:

- Vertical rail-wheel force, V (left and right wheels)
- Lateral rail-wheel force, L (left and right wheels)
- Ratio of lateral force over vertical force, L/V (left and right wheels)

For the sake of convenience, the left and right wheel of IWS02 are denoted as Lead-Left and Lead-Right, respectively. By the same convention, the denotation Trail-Left and Trail-Right wheels are used for IWS01. "Lead" and "Trail" are used to refer to the truck location instead of axle locations. Note both the IWS's are the leading axles of the corresponding truck.

2.4. Data Acquisition System and Recorded Datasets

The data acquisition system used in the tests was a MEGADAC. It recorded all the geometry and force channels described in the previous subsections simultaneously. The data were saved on an optical disk and they can be played back and transferred to many other data formats after the tests. The data sample rate used in the tests was 150 Hz. The filter in the MEGADAC was chosen as 30 Hz.

The field data of 292.8 miles were recorded into 20 different datasets. Excluding some bad signals and some short datasets generated from several trial or repeated runs, Table 2 shows 12 datasets used in the present analysis, which cover 92% of the recorded data (268.8 miles). The starting mileages shown in the table were obtained by comparing the recorded curvature with BC Rail's Condensed Profile [1]. The total mileages and the end mileages listed in the table were obtained by integrating the Speed channel.

2.5. Track Conditions

The track used in the tests was continuous welded wooden-tie track, with a total length of about 300 miles. This track is located in the mountain territory of British Columbia, Canada. There are many curves, and several tunnels and bridges on the track. There are wayside lubricators installed on many curves. Only some of them were functioning properly during the tests, as determined by BC Rail personnel. On the day of the tests, the temperature in the morning was 4 to 7°C.

3. DATA PROCESSING

3.1. Distance-based Channels

For the comparison between the geometry defects and the force events, which were recorded at the different locations in the test trains as shown in Figure 2, some distance adjustments for the compared channels are essential.

However, the original data recorded by NRC-CSTT's data acquisition system for both geometry channels from CN's track geometry car and force channels from IWS are time based. This makes it difficult to do distance adjustment properly, as the test train was not always traveling at a constant speed. Therefore, pre-processing needs to be done to transfer all the time-based channels into the distance-based channels.

A program was developed to do the transfer automatically. First a distance (mileage) channel was built by integrating the speed channel recorded from geometry car. The starting mileages for each test-recorded dataset used in the integration are from Table 2. The relations between measured geometry or force values and time were then mapped to *X*-*Y* relations between the values (*Y*s) and distance (*X*). Finally, the *X*-*Y* relations with a non-constant *X* interval were linearly interpolated into ones with a standard (constant) X interval. The last step is necessary because only a constant interval relation can be numerically processed robustly in the DADiSP (**D**ata **A**nalysis and **Disp**lay – a commercially available signal processing software package) system. A constant distance interval of 0.000025 mile (1.584 in.) was used in the interpolation. This interval is small enough to ensure there is no loss of frequency component of interest.

3.2. Test Track Breakdown

To determine the track type (tangent, spirals or curve body) where a specific geometry or force defect occurred, the test track was broken down into different sections according to the raw curvature data obtained from the geometry car. A program was developed to help do this. The starting and ending points of each track section were manually chosen by mouse clicks on the curvature channel plot shown in a displaying window of the program. The tangent track section was idealized as zero degrees of curvature, the curve body section as a constant degree equal to the average value of the measured degrees in the section, and the spiral section as a straight line connecting the ends of the tangent (or curve) and curve sections.

The obtained type (tangent, spiral or constant curve) and direction of curve, the average degree of curve track and the positions of each section were stored in a database table automatically from the program. Table 3 shows part of the track section table. Figure 3 shows the comparison of the measured track curvature with the one built up according to Table 3 for a short part of the tested track. A good agreement between the measured track and the idealized one can be seen. Such comparison has been conducted for all the tested track to confirm the agreement.

The track section table is used frequently in later analysis for identifying the track type and for grouping parameters by track curvature, etc.

3.3. Building Continuous Track Geometry Channels from Geometry Car Raw Data

The CN geometry car's track exception report [2] provided by BC Rail is the reference data used to identify geometry defects for comparison with wheel-rail force events in this investigation. This exception report provides a set of track defects detected according to current industrial practices (Transport Canada Track Safety Rules). One of the main problems, when using this set of geometry data in the present investigation, was the difficulty of synchronizing it properly and accurately with the IWS force channels in the distance base.

The available raw data of all the geometry car channels, recorded simultaneously with the IWS force channels in NRC-CSTT's acquisition system, provide another option to obtain the track defects: i.e., building continuous geometry channels directly from the raw data and then detecting the track defects by using a relevant track standard. This option has three advantages: (1) automatic synchronization between the built geometry channels and NRC-CSTT's force channels in time and distance bases; (2) full flexibility to obtain the track defects based on the relevant track standards such as Transport Canada's Track Safety Rules and BC Rail's internal track standards, etc.; (3) benefit for a continuous comparison between geometry and force parameters.

Therefore, the geometry defects used in the analysis of this investigation were those built directly from geometry car raw data recorded in NRC-CSTT's data acquisition system. Since the track alignment measurement was not available in the field test as described in Section 1, the track defects used in the analysis were several track surface variations widely used in the industry, including Vertical Rail Surface Profile, Cross Level, Warp and Twist.

These geometry parameters were built and stored as separated channels in the project's database. The procedures and method to derive these geometry parameters from the raw data, according to the definition in Transport Canada's Track Safety Rules [3], are described as follows.

- ***Profile 62' Chord***

According to the Transport Canada Track Safety Rules, the profile defect is defined as "the deviation from uniform profile on rail at the mid-ordinate of a 62 foot chord". Hereafter, this profile defect will be denoted as "***Profile62***".

There are two raw profiles, left and right, available from the CN geometry car. These are track surface irregularities recorded directly based on the measurement of axle box accelerations. The Profile62 defects were derived from the raw profile data as

$$\mathit{Profile62}(X) = \text{RawProfile}(X) - [\text{RawProfile}(X + 31') + \text{RawProfile}(X - 31')\,] / 2 \qquad (1)$$

where X denotes any location in the test route and will be used hereafter. This operation has been applied to both left and right rails to get the left and right channels of Profile62.

- ***Cross-Level***

The definition of Cross-Level in the Track Safety Rules is “deviation from zero cross level at any point on tangent or from designated elevation on curves between spirals”. By this definition, this defect was calculated by the difference between the left and right raw profile measured, that is

$$CrossLevel(X) = |\ \text{RightRawProfile}(X) - \text{LeftRawProfile}(X)\ | \qquad (2)$$

where |.| denotes the absolute value operation and will be used hereafter.

Another more commonly used method to obtain the Cross-Level defect is based on the superelevation data. To apply this method, the data of the designated superelevation for the tested curve and spiral tracks are required for comparison with the measured superelevation.

Since the designated superelevation for the tested BC Rail track was not available in the raw test data, the superelevation-based method was not applied in this investigation. The impact of using the profile-based method instead of the superelevation-based Cross-Level on the present investigation is discussed in subsection 4.2.2.

- ***Warp 31'***

The defect defined in the Track Safety Rules as “variation in cross level on spirals in any 31 feet” is called “***Warp31***” according to a general industrial convention. Another raw data channel, Superelevation, was used to calculate this defect according to the following formula:

$$Warp31(\text{X}) = |\ \text{SuperElevation(X)} - \text{SuperElevation(X} - 31')\ | \qquad (3)$$

By definition, Warp31 is a geometry defect only applied to a spiral track section. In the defect statistics and comparison analysis, the track section table shown in Table 3 is used to exclude the defect value outside the spiral section.

- ***Twist 62'***

Another track surface defect due to changes of cross is call twist. According to the Track Safety Rules, this defect is defined as “the difference in cross level between any two points less than 62 feet apart on tangents and curves between spirals”. Hereafter this defect will be denoted as “***Twist62***”.

Exactly following the above definition, Twist62 was derived from the raw data of the measured superelevation. The procedure used for the calculation was as follows:

For each track location X, (1) Calculate the maximum and the minimum values of Superelevation between X and (X – 62'), and denote them as Smax and Smin, respectively; (2) Calculate the Twist62 by

$$Twist62(X) = \text{Max}\{\ |\text{SuperElevation}(X) - S\text{max}|,\ |\text{SuperElevation}(X) - S\text{min}|\ \} \qquad (4)$$

where Max{A, B} means the maximum value among A and B.

3.4. Building Channels for Force Parameters

The most likely mode of derailment for an empty tank car is a wheel climb derailment. Other modes of derailment, such as dynamic wide gauge, rail rollover, and low speed harmonic roll, are generally associated with heavily laden, high centre-of-gravity cars. They are not appropriate for inclusion in this investigation, since the test car was an empty tank car.

Denoting *L* as the wheel lateral force and *V* as the wheel vertical force, wheel climb derailment can be predicted by the wheel *L*/*V* ratio, and is generally caused by low *V*, or combined increased *L* and low *V*. The current AAR Specification M 1001, Chapter 11, a standard generally accepted by industry, specifies the peak ***Wheel L/V Ratio*** and ***Retained Vertical Wheel-Load Ratio*** (expressed as a percentage of static wheel load) as two derailment parameters. Therefore, these two parameters are included in the present analysis.

The angle of attack of the wheelset has a significant bearing on the actual wheel L/V ratio necessary to initiate wheel climb. With low or negative angles of attack, the critical wheel L/V ratio is increased significantly above the lower bound Nadal value. This was recognized by Weinstock (1984) [4], and the ***Axle Sum L/V Ratio*** was used to account for the effect of low axle angle of attack values, commonly encountered on tangent and shallow curvature alignments. As a measure of vehicle derailment propensity due to increasing track curvature, the AAR Chapter 11 axle sum values are also included in this investigation.

Using the IWS raw data recorded in NRC-CSTT's data acquisition system, the above three force parameters were easily built into separated channels of the project's database as follows.

- ***Wheel L/V Ratio***

This parameter was available directly from the IWS's raw data, which was calculated from the *L* and *V* forces during the test. There are four channels corresponding to four wheels for this parameter.

- ***Retained Vertical Wheel-Load Ratio***

This parameter was obtained by dividing the vertical force *V* by the static wheel load *V0*. As the empty tank car weighed 100,100 lb., *V0* is equal to 12,513 lb. Thus, if the Retained Vertical Wheel-Load Ratio is denoted as "***%Vforce***", then

$$\%Vforce = V \,/\, V0 \qquad (5)$$

- ***Axle Sum L/V Ratio***

By definition, the Axle Sum L/V Ratio is the absolute sum of the individual wheel L/V's on the same axle, as given in the following algebraic equation:

$$\text{Axle Sum } L/V = |\, L/V \text{ (Left wheel)} \,| + |\, L/V \text{ (Right wheel)} \,| \qquad (6)$$

It should be emphasized that, although the force defects defined above referred to AAR Chapter 11 specifications for acceptance of a new built car, the dynamic rail-wheel forces, such as wheel L/V and vertical force unloading ratio, are general derailment criteria for all kinds of railway cars on track, new or old. Relating geometry defects to these wheel-rail force criteria can provide a more insightful understanding about the impact of curvature on geometry safety standards from derailment point of view.

3.5. Database Channel Summary and Offset Distance Adjustment

Table 4 summarizes all the continuous geometry and force channels processed above. There are 9 track geometry channels and 18 force channels in total. All of these data are stored in the project database in DADiSp 2000 format, and can be accessed and controlled by a user-friendly interface written in Visual Basic for Application. The ActiveX connection package of DADiSp 2000 was employed to build the connection between the interface and the database.

All the geometry and force channels were built or transferred into distance (mileage) based ones. The transfers were done by the method described in subsection 3.1, without considering the distance difference between the locations where these channels (or their raw data) were recorded. Please refer Figure 2 for locations of the measured channels.

The distance adjustment is done when comparing data in different channels, by using the value of the distance difference from the centre of the geometry coach car for each channel listed in Table 4. This value has been calculated based on the car dimensions given in Table 1.

4. COMPARISON OF GEOMETRY AND FORCE DEFECTS

4.1. Some Statistics of Track Curvature

From the track section data listed in Table 3, some statistics of the test track used in the following analysis can be obtained. Table 5 gives the number of track sections for each track type, i.e. tangent, curve and spiral. From the track section point of view, about 80% of the test data was obtained on curve track, including curve body and spiral sections. This reflects the feature of BC Rail's mountain territory rail track and is beneficial for the present investigation on the track curvature effects on the track safety standards.

Figure 4 shows the curvature distribution of all the curve-body track sections. While most of the curve track sections have a curvature between 2 degrees and 8 degrees, there are some sections with very high degrees of curvature (> 10 degrees).

Since the statistics in Table 5 show that the total length of the tangent track sections is about the same as that of the curve/spiral sections, the average length of the curve/tangent sections is shorter than that of the tangent sections. This can be seen more clearly in the length distribution of the tangent and curve track sections in Figures 5 and 6, respectively.

4.2. Track Standards and Surface Defects Scanning

4.2.1. Track Standards

One of the main track standards used in this investigation was Transport Canada's Track Safety Rules [3]. Additionally, BC Rail has an internal track standard for urgent track defects [6], which is based on both Transport Canada's rules and the "Railway Safety Code" of the Ministry of Transportation of British Columbia (BC Transport) [5]. To clarify the difference between Transport Canada's standard and BC Rail's urgent track standard, a comparison among the three track standards is given in Table 6.

Only the geometry parameters like Profiles, Cross-Level, Warp31 and Twist62 described in subsection 3.3 are compared in Table 6. It can be seen that, for Cross-Level and Profile62, BC Rail's urgent standard is generally more restrictive than the Transport Canada's standard. In the case of Warp31, BC Rail has tightened the defect limits significantly from Transport Canada's limits in order to reduce derailments and improve track safety. For the cross level variation in 62 feet or less (Twist62), the BC provincial standard is less restrictive than Transport Canada's. It also introduces the difference in standard between curve track and tangent track, allowing the limit values on tangent track for Twist62 to be considerably larger than on curve track. Following the BC provincial standard, BC Rail's urgent standard also has two sets of limits for Twist62, but the limits for defects on curve track were tightened to a level lower than Transport Canada's standard.

The two track standards applied in this investigation were the Transport Canada standard and the BC Rail urgent standard. As BC Rail's urgent track limits are generally tighter than Transport Canada's, they were used as the "Priority" defect standard, and Transport Canada's rules were used as the "Urgent" defect standard for the purpose of this investigation.

The words “Urgent” and “Priority” are used hereafter to denote two different levels of defect. The defects were scanned out by two different threshold values and then compared with the IWS’s force events. This is a little different from the convention used in the railway industry, because all the “Urgent” defects are also in the “Priority” group. In the industry, “Urgent” means the defect is critical and needs to be repaired immediately before the next train passes, or the track operating speed must be reduced to that of the next lower class that can accept operation with the defect present. “Priority” means the defect is not yet at the critical level but a repair action needs to be scheduled. In this case, the “Priority” group does not contain the “Urgent” group.

When using BC Rail’s urgent standard, only the limit values for curve track were used; i.e., this set of limits was used for both the tangent and curve tracks. This is because the same comparing base was needed when comparing the defects on curve and tangent tracks.

4.2.2. Track Defect Scan

The track geometry channels in the database were scanned to determine the “Urgent” defects based on Transport Canada's track standards, and the "Priority" defects based on BC Rail's urgent defect limits. The scanning method was as follows:

(1) The geometry channels of Profiles, Cross-Level, Warp31 and Twist62 recorded in the project database were scanned track section by track section, with each track section defined in Table 3;
(2) The track class of each section was determined by referring to the freight car speed limits in Table 7, cited from BC Rail's "Prince George Subdivision Footnotes" and "Lillooet Subdivision Footnotes" issued April 27, 1997 [7];
(3) Geometry defects were determined by comparing the peak values of geometry channels in the scanned track section with the limit values of the track standards corresponding to the track class of the track section;
(4) The “Urgent” defect was obtained based on Transport Canada's track standards, and the "Priority" defect based on BC Rail's urgent defect standard;
(5) The distance coordinate of each geometry channel scanned was shifted to the centre of the CN geometry coach. When a defect event was found, its value, location, curvature of the track, etc. were recorded.

Scanned results showed that there existed no “Urgent” or “Priority” Profile and Cross-Level defects in the track tested, which is in general agreement with the exception report of the geometry car [2]. The result that there was no single Cross-Level defect for about 269 miles of track was rather surprising. One possible reason is the use of the Profile-based method. It is expected that some Cross-Level defects could be detected if the Superelevation-based method were applied.

Hereafter, the track defects discussed are only Warp31 and Twist62. Tables 8 and 9 show all the “Urgent” defects. Table 8 is for Twist62 both on tangent track and on curved track, and Table 9 for Warp31 on spiral track. All the scanned results for “Priority” Twist62 and Warp31 defects are shown in Tables 10 and 11, respectively.

When counting the defect number, it was found that the most of the track defects occur on the spiral sections. There were 396 Warp31 defects out of the total 446 defects in the case of “Priority” standard, and 34 Warp31 defects out of the total 52 defects in the ”Urgent” case.

Another observation from the defect number is that there were more Twist62 defects on the curve track than on the tangent track.

4.2.3. Comparison with Geometry Car Report

The urgent geometry defects shown in Tables 8 and 9 were compared with those listed in CN Geometry Car's "T.E.S.T. Urgent Exception Report [2].

For Warp31 defects at the "Urgent" level, the CN Report [2] shows 78 defects on Transport Canada class 3 track and 14 defects on class 4 track. Compared with this, the present analysis shows only 31 defects on class 3 track and 3 defects on class 4 track. To examine the difference, the values of the Warp31 defects in the CN Report and those in Table 9 were checked. For defects on class 3 track, it was found that the minimum value of Warp31 in the CN Report is 1.07 in. and the minimum value in Table 9 is 1.251 in. From Table 6, one can see that the limit value of Warp31 for class 3 track is 0.75 in. for BC Rail's urgent standard, 1.00 in. for the BC provincial standard and 1.25 in. for the TC Standard. Therefore, there is a possibility that CN Report and the present analysis are based on different standards.

4.3. Wheel "Force Defect" Definition and Force Defect Scanning

The critical values (at which derailment risk increases) for the force parameters such as Wheel L/V Ratio, Axle Sum L/V and Retained Vertical Wheel-Load Ratio, are defined in AAR Specification M1001, Chapter 11. Although a little conservative, they are well accepted by the industry. Thus, the **Urgent Force Defects** are defined by these values, i.e.:

Wheel L/V Ratio = 1 (7)

Axle Sum L/V = 1.5 (8)

Retained Vertical Wheel-Load Ratio (%) = 10 (9)

Naturally, the urgent force defects are compared with the urgent track geometry defects.

However, in order to compare the less critical geometry defects defined by BC Rail's standard (i.e., the "priority" geometry defects), a more conservative force criterion was needed to define the corresponding priority force defect. This was done by arbitrarily introducing an 80% rule. The "**Priority" Force Defects** are defined as

Wheel L/V Ratio = 0.8 (10)

Axle Sum L/V = 1.2 (11)

Retained Vertical Wheel-Load Ratio (%) = 28 (12)

Note that the meaning of the words "Urgent" and "Priority" is slightly different from the industry convention as explained in subsection 4.1.1.

Following the similar method described in subsection 4.2.2 for geometry defect scanning, the force defects were scanned, section by section. For each force parameter, there was more than one channel recorded for the different wheels or axles. In the case of the Wheel L/V Ratio, the maximum value of the L/V ratio among those of the four different wheels, i.e. leading left, leading right, trailing left and trailing right, was found and used as a single channel for scanning the force defects. The same procedures were applied to the Axle Sum L/V ratio and Retained Vertical Wheel-Load.

The resulting force defects are shown in Tables 12 and 13. For the “urgent” force defects based on AAR Chapter 11 limits, there were only eight defects found; one was on tangent track, one was on spiral track, and other six were on curved track, as shown in Table 12. For the “priority” force defects with the 80% rule applied to Chapter 11’s limits, Table 13 lists 8 defects on tangent track, 39 defects on curve track and 23 defects on spiral track. Remember that these “priority” force defects occurred under an empty tank car, and that other car types might have a different force defect response to the track geometry.

4.4. Comparison of Occurrence Rate of Geometry Defect and Force Defect

Tables 14 and 15 compare the number of geometry defects with that of force defects, at both the “urgent” and “priority” levels. The defects are grouped according to the type of track. Since there exist no other kinds of defects except Twist62 and Warp31, the defects that occurred on tangent and curve tracks are only Twist62, and the defects that occurred on spiral tracks are only Warp31.

For both tangent and curve tracks, the “urgent” Twist62 defect was detected by using the threshold value according to Transport Canada’s track standards. This is true also for the “priority” Twist62 defect detected mainly following BC Rail’s standards, although there exist different threshold values for tangent and curve tracks in BC Rail’s track standard. In the “priority” case, the employed threshold value was the one defined for curve track as described in subsection 4.2.1.

Tables 14 and 15 show that there are many more geometry defects than force defects. At the “urgent” level, the total number of geometry defects detected is 52, compared to 8 force defects of all types. At the “priority” level, the geometry and force defect numbers are 446 and 70, respectively. This means the overall occurrence rate of geometry defects is about six times higher than that of force defects.

Calculating the ratio of total number of force defects over that of Twist62 defects, on tangent and on curve tracks, one can find that there are more force defects per unit Twist62 defect on curve track than on tangent track. In the case of the “urgent” defect level, the ratio on curve track is five times larger then on tangent track. For the case of the “priority” defect level, which is statistically more reliable because of the larger defect number, this ratio on curve track is three times larger than on tangent track.

The above comparison provides supporting test evidence for curvature effects on track standards used in this investigation, which indicates that, with the same level of Twist62 geometry defects, the curved track produces more force defects than the tangent track. This test evidence supports BC Rail’s practice to use a looser geometry threshold value of Twist62 defect on tangent track than on curved track.

For Warp31 defects on spiral track, Tables 14 and 15 show that the occurrence frequency is much larger than that of force defects detected by the IWS. This indicates that, if only from a wheel force point of view on an empty tank car, the threshold values of Warp31 defects specified in the track standards may be too tight. To further explore the curvature effects, the Warp31 defects and the force defects were grouped according to degree of the curves that the spirals go to or leave from. The ratio of the force defect number over the Warp31 defect number is then calculated for each group. The results are shown in Figure 7. There is a clear tendency that the detected force defects per unit Warp31 defect increase as the degree of curve increases.

4.5. Correspondence of Geometry Defect and Force Defect Events

To obtain the location correspondence of geometry defect and the force defect, force defect scanning was conducted for a range around the location of each geometry defect event listed in Tables 8 to 11.

If the location of a geometry defect is noted as *Xg*, the scanning range for the force defect is from 30 ft. behind *Xg* to 195 ft. after *Xg*. The distance of 195 ft., used in the range (after the geometry event), is to cover the possible history-dependent effect of the geometry defect on the wheel force. Another distance of 30 ft. is used to consider possible error of distance match between the geometry and force channels. Before scanning, the distance coordinate of the force channels was shifted to the centre of the geometry car coach by using the distance difference shown in Table 4. Note that the location coordinates of geometry defects in Tables 8 to 11 are already adjusted.

Scanned results show that the location of

- 52 “Urgent” geometry defects vs. 8 “Urgent” force defects
  1 pair matched

- 446 “Priority” geometry defects vs. 72 “Priority” force defects
  13 pairs matched

The three different matching categories, i.e. force defects with corresponding geometry defects, geometry defects without corresponding force defects, and force defects without corresponding geometry defects, are discussed in the following subsections. However, a brief discussion is first conducted to address the surprisingly small number of matched force-geometry defect pairs.

For all the detected force defects, above results show only a very small percentage of them having a matched geometry defect. The question arises whether there exists any correspondence between the force defects and geometry defects investigated here. This is answered by a general discussion in subsection 4.5.3 and by detailed discussions for each of eight “urgent” force defects in Appendix A. These discussions show that:

- Most force defects corresponded to certain variations of track geometries.

- In many cases, force defects were produced by combinations of two or more geometry variations that had an individual error value smaller than the track standards.

- In some cases, force defects were mainly due to a track alignment defect, which is not available in this investigation.

4.5.1. Matched Geometry and Force Defects

Table 16 shows all 13 matched pairs of geometry and force defects at the “priority” level. The one matched pair for “urgent” geometry defects against “urgent” force defects is indicated in the table in bold type. Among the 13 pairs, nine matched events occurred on spirals and two occurred on curves. No matched events were found on tangents.

By using the limited number of the above matched defect pairs, some tentative analysis has been done to explore the effects of the curvature of track on the relation between geometry defects and force defects.

Three cases are plotted in Figure 8 for the relation between the Retained Vertical Force and Warp31. The first case assumes that the Retained Vertical Force depends on the Warp31 defect only. It can be seen that the correlation of the relation is not good in this case. The correlation becomes better in the second case, which assumes that the Retained Vertical Force is dependent on both the Warp31 defect and the degree of curvature of track. Obviously, the best correlation is obtained by the third case, which assumes that the Retained Vertical Force is dependent on both the Warp31 defect and the cant deficiency. The results shown here, although derived from a quite limited number of data, indicate that the track curvature, especially combined with car speed and superelevation, does have important effects on the relation between geometry defects and force defects.

Figures 9 and 10 are similar plots to relate Warp31/Twist62 to Wheel L/V ratio and Axle Sum L/V Ratio, respectively. It can be seen that there exists no good correlation between the geometry defect and the force defect, even after including the effects of track curvature or cant deficiency. This will be further discussed in subsections 5.1 and 5.3.

Figures 11 to 13 show three typical history profiles for the geometry-force corresponding events. The channels shown in the plots include the corresponding geometry and force defects, as well as the idealized track curvature defined in Figure 3. The correlation and correspondence between geometry and force defects can be seen clearly in these plots.

4.5.2. Geometry Defect without Corresponding Force Defect

Tables 17 and 18 give the number of geometry defect events that have no corresponding force defect events at “Urgent” and “Priority” levels, respectively. In analyzing these events, the question arises that if the geometry defect is not traversed at the maximum speed for the class of track assigned, will a large force defect occur? The premise on which the track geometry standards are based assumes that reducing speed through a geometry defect will reduce the risk of a large force defect. Traversing a Class 3 geometry defect at 25.1 mph may result in lower dynamic wheel-rail forces than if the same defect were traversed at 40 mph. Therefore, it is argued that the geometry defects having been traversed at the low end of the speed limit of the track class should be excluded from the analysis. To do this, two speed rules are introduced in Tables 17 and 18.

Rule 1 is to remove those geometry defects that were traversed at a speed lower than 90% of the speed limit of the track class. This produced 320 "valid" geometry defects at the "Priority" level from the original 446 events. However, when applying this rule to the geometry-force matched events listed in Table 16, it was found that 6 pairs out of the total of 11 pairs of matched events had very low traversing speeds and do not follow this speed rule. This indicates that **speed itself may be not enough to measure the dynamic effects**, especially on curves or spirals.

Cant deficiency (CD) is used as the criterion for Rule 2, the criterion that CD > 1.5 in. for valid events. The value of 1.5 in. is just half of the 3 in. cant deficiency allowed in Transport Canada's Track Safety Rules. Rule 2 removes more geometry defects than Rule 1 and the "valid" defects reduce to 172 events from the original 446 for "Priority" case.

Even for the case with the least "valid" geometry defects based on Rule 2, Tables 17 and 18 show that most geometry defects do not have corresponding force defects. This result indicates that the track standards for geometry defects are tighter than the AAR Chapter 11 criteria for force defects, based on the IWS results for the tested tank car.

Three typical history plots for three "urgent" geometry defect events without corresponding force defects are shown in Figures 14 to 16. All the force defects around the geometry defect are shown. Among them, not one reaches a value larger than "priority" (80% of AAR criteria) level. These results show that the existence of a geometry defect does not necessarily lead to a high dynamic force for the empty tank car tested here.

4.5.3. Force Defect without Corresponding Geometry Defect

This is the case that has exceeded the scope of this project. However, some discussions are given below for future investigation.

Table 19 gives the number of force defects with and without corresponding geometry defects at both the "urgent" and the "priority" levels. The percentage of the force defects without corresponding geometry defects is quite large. Since an important type of geometry defect, track alignment, was not included in the present correspondence analysis, it is possible that some corresponding pairs in which a force defect is produced by an alignment geometry defect were not counted.

Figures 17 to 20 show some typical history plots for force defects in which no geometry defects, defined in the previous sections, were found. In each plot, in addition to the force channel that presents the force defect, all the geometry defect channels available from the field test are shown. The following three different cases were identified for further investigation.

(1) No geometry defects were found to explain a sharp increase of the dynamic force, as shown in Figure17.

(2) No track surface defects were found, but a track gauge (wide gauge) defect was found as shown in Figure 18. Although the wide gauge is not usually considered to have direct effects on wheel vertical or lateral force, the large change of the gauge can be seen as

an indicator for a possible track alignment defect [8]. Therefore, this case could be considered as alignment-induced force defects.

(3) As shown in Figures 19 and 20, the track surface variations around a force defect do exist, but are not large enough to be detected as defects according to the track safety standards. It seems that, in this case, the effective value of a track surface variation is enlarged from its geometry value so as to produce a force defect. The enlargement may be due to various effects, including a sharp curve on the track (for example, Figure 19), or to the history dependence of several repeated waves of geometry variation, or to the combination of geometry defects of different types, etc.

5. GENERAL RELATIONS BETWEEN TRACK GEOMETRY AND WHEEL FORCE RATIO WITH TRACK CURVATURE EFFECTS

With quite limited data points available, the relation between geometry defects and force defects at the "priority" level was explored in subsection 4.5. Some interested tendencies about the effects of track curvature are shown in Figure 8.

To further exploit these findings, a more general relation between track geometry and wheel force ratio was investigated based on peak values of the measured parameters in each track section. Since there are more than 3,000 track sections in total (see Table 5), the results are statistically more reliable. On the other hand, the peak value in a track section for geometry parameter or force parameter may be less than the threshold value for a "defect" defined by track standards or AAR Chapter 11. Thus, the relation investigated here is more general, and not limited to a certain defect level.

5.1. Correlation between Track Geometry Parameters and Wheel Force Ratios

Data used for the investigation on the general correlations between track geometry and wheel force ratio were obtained by the following processes.

(1) From all the track sections listed in Table 3, the peak values and the locations of the peak values were scanned out for all the interested track geometry parameters including Warp31, Twist62, Profile, Cross-Level and Track Gauge.

(2) For each of the above geometry parameters, a scan to find the maximum (or minimum) value of all the wheel force ratios was made using a track range from 30 ft. behind to 195 ft. after the location of the peak value of the parameter. The three force ratios are Retained Vertical Force Ratio (%), Wheel L/V Ratio and Axle L/V Ratio. The maximum or minimum value among the four wheels or two axles of each force ratio was further obtained for the following relation studies.

Using the data obtained above, the correlation coefficients of relations between each of the geometry parameters and force ratios were calculated. The results are shown in Table 20. According to its definition, the correlation coefficient is a measure of how strongly two variables are related, and it qualifies the degree of linear association between two variables. Thus, results shown in Table 20 indicate that for the tank car tested,

- The vertical wheel force ratio (% retained load) is reasonably dependent on track surface variations such as Warp31 and Twist62. The best correlation is between wheel vertical force and Warp31 on spiral track as shown in Figure 21.

- There is almost no dependence between wheel L/V ratios and the track surface variation parameters (Warp31, Twist62, Profiles and Cross-Level). A typical relation with poor correlation relation is shown in Figure 22 for Twist62 and Axle Sum L/V ratio on tangents.

- Track Gauge shows some correlation with wheel L/V ratio. This reflects a possible strong relation between track alignment and wheel lateral force, since track gauge itself has some correlation with single-rail alignment [8].

5.2. Effects of Track Curvature

It can be seen that, even for the most dependent relation discussed above, i.e. between Warp31 and Retained Vertical Force Ratio, its correlation coefficient is still too low to be considered as a good linear relation. Generally speaking, the vertical wheel force is a function of many factors, including all the track geometry parameters, track curvature, car speed, track subgrade stiffness and maybe the previous dynamic history of car movements. A large scatter band as shown in Figure 21 is not unexpected when this complicated function is simplified by a linear relation between vertical wheel force and Warp31. This argument is also true for other wheel force parameters such as wheel lateral force and L/V ratios. To improve the relation between wheel force parameters and track geometry parameters, more variables that have important effects on the wheel force need to be included. As expressed in the basic idea that initiated this investigation, track curvature is the factor needed to be considered first.

There is a lot of previous research on the steady-state curving of a rail car on a mathematically smooth track without any surface or alignment variations [8]. According to this research, curving will lead to a considerable level of steady-state lateral force or L/V ratio due to friction creepage or flange contact during curve negotiation. Also, it was found that the steady-state wheel lateral force and therefore L/V ratios increase as the degree of track curvature increases [8].

In the present field test for a tank car, there exists no real steady-state value for the wheel forces because of the various disturbances from track geometry variation. However, the average level of measured force can be considered as an approximate measure of the steady-state values. Figure 23 is a typical case that shows how the average level of lateral wheel force changes following the change of track curvature.

To further show the effects of degree of curvature on the AAR force ratios from the present tank car test, the **average value** of Wheel L/V Ratio was calculated for tangent and curve body track sections longer than 1000 ft. The shorter sections were excluded because the effects of the previous unsteady history, such as spiraling, significantly affect the average value. This reduced the total number of track samples to be included to 244, with 184 tangents and 60 curves (see Figures 5 and 6 for the statistics of track section length). Figure 24 shows the result. The L/V ratios for the leading axle of the leading truck and for the leading axle of the trailing truck are both included in the figure. A relatively good linear correlation between the average L/V ratio and curve degree is obtained. The result indicates the “steady-state” L/V ratio increases about 0.05 per degree. This means an 8-degree curve will have a wheel L/V ratio of 0.5 even without any disturbance from track geometry defects. Assuming a geometry defect (like alignment) contributes another 0.5 increase of the L/V ratio for both the tangent and the 8-degree curve tracks, the wheel force on the curve track now arrives at a critical level for wheel climbing derailment, while its value on a tangent track is still at quite a safe level (about 0.5).

The above analysis shows again the need to use different track geometry threshold values for curved and for tangent tracks, as well as for curved tracks with different degrees of curvature. To obtain a quantitative estimate of the difference of the threshold values for each type of geometry defect, reliable relations among wheel force ratio, track geometry variance, track curvature, etc. need to be established first.

For Retained Vertical Force Ratio, a relation is used in Figure 8 to relate the force ratio to Warp31 and Cant Deficiency. A more general expression for the relation can be written as

$$\text{(Retained Vertical Force Ratio)} \propto \text{(Warp31)} * \text{(Cant Deficiency)}^{m} \qquad (13)$$

Where Cant Deficiency is calculated using local superelevation and car speed at the location where a Warp31 event occurs, following the definition in the Track Safety Rules [3].

The index *m* is introduced to adjust the effect of curvature (as well as speed and superelevation). Some optimization trials show that, when using the above equation with *m* = 0.5 to fit the test results as shown in Figure 21, the correlation coefficient can be increased to 0.632.

As for the wheel L/V ratio on tangents and on curves, a relation with the following form is tentatively suggested based on the results shown in Figure 24.

$$\text{Wheel L/V Ratio} = 0.05 * \text{(Degree of Curve)} + C * \text{(Alignment)} * \text{(Cant Deficiency)}^{n} \qquad (14)$$

Where *C* and *n* are constants to be determined. Track alignment is used here because the other geometry parameters studied in Table 20 show almost no correlation with L/V ratio, and some simulations shown in the next subsection indicate a strong correlation between L/V ratio and the track alignment.

5.3. Wheel L/V Ratio and Track Alignment

Table 20 shows very weak dependence of wheel L/V ratios on all the track geometry parameters studied. A little better correlation of L/V ratio with gauge implies the importance of track alignment. To further confirm the existence of a strong relation between track alignment and wheel L/V ratio, some preliminary computer simulations for the tank car running on a track with given alignment defects were conducted using NUCARS, an AAR-approved software package for performing dynamic simulation of a rail car.

A NUCARS model of the tank car was built based on the available data of empty tank car weight, car dimensions and standard Barber S-2 truck specifications. The main load spring data was calculated by using the AAR manual [9] for the 7-outer-6-inner spring nest group configuration used in the car. A variable damping friction wedge was included by using the available spring stiffness and estimated friction coefficient. The wheel-rail profile table used was for new AAR1B wheel with a back-to-back distance of 53.047 in. and 136 lb. rail with 14 in. crown radius, 1/40 cant and 56.5 in. standard gauge. The coefficient of friction between track and wheel was given as 0.5.

The track regime used for the simulation was a 200 ft. tangent track with a double-rail (symmetric) misalignment of sinusoidal type with a wave length of 39 ft. and an amplitude ranging from ¼ in. to 2 in. The empty tank car was run in the simulation at a constant speed equal to 45 mph.

The simulation result is shown in Figure 25 for the maximum Wheel L/V Ratio as a function of the amplitude of track alignment. The result clearly gives a strong dependence of Wheel L/V Ratio on Track Alignment. By having the slope of the relation approximately equal to 1/1.5, it can be used as a very rough estimate for the constant *C* in the previous Wheel L/V ratio equation. It is interesting to note that the threshold values specified by the track safety standards are at a level to produce a simulated Wheel L/V ratio equal to the AAR Chapter 11 criteria.

6. CONCLUSIONS

Based on a detailed analysis of 269 miles of field data for an empty tank car on BC Rail's main line, the present investigation produced the following observations, results and conclusions:

(1) The overall occurrence rate of geometry defects defined by Transport Canada's track standard or BC Rail's urgent standard is about six times higher than that of the force defects defined by AAR Chapter 11 criteria, or 80% of the AAR criteria (see Tables 14 and 15). This indicates that:

> **The threshold values of the studied track standards are generally more restrictive than that of the wheel force criteria of AAR Chapter 11 for the empty tank car.**

(2) For the same number of Twist62 defects, the occurrence of instrumented wheel force defect events on curve track is more than two times larger than that on tangent track (see Tables 14 and 15). For the same number of Warp31 defects on spirals, the occurrence of instrumented wheelset force defect events increases as the degree of curve increases (see Figure 7). These results, together with other observations of the present investigation (as shown in Figures 23 and 24), suggest the following argument:

> **The threshold values of Warp31 and Twist62 on spiral/curve track with higher degrees of curvature should be more restrictive, while the threshold values on tangent track or spiral/curve track with lower degrees of curvature could be less restrictive for an empty tank car.**

(3) An equation (Equation 13) that relates the Retained Vertical Load ratio to Warp31 and Cant Deficiency on spirals was developed and partially confirmed from the present analysis of the field test data. Another equation (Equation 14) to relate Wheel L/V Ratio to Track Alignment was suggested, based on the test result correlation between steady wheel L/V ratio and curve degree, and on the NUCARS simulation result on the relation between Wheel L/V Ratio and Alignment:

> **These equations, with further test or simulation confirmation and possible refinement, could be used as tools to quantitatively evaluate the effects of track curvature on the threshold values of track geometry defects in any future study of revision of track geometry standards. The data and analysis to date has been limited to an empty tank car.**

7. RECOMMENDATIONS

Preliminary results indicate that the investigation of the importance of track curvature on the Track Safety Standard, by an approach relating limiting values of track geometry parameters to car derailment force parameters, is a promising research direction for railway safety. Therefore, further research in this direction is strongly recommended. Some future work to be done could include:

(a) Further investigation into the relations between track alignment defects and wheel force defects like L/V ratio.
(b) Investigation into the effect of different car types other than an empty tank car.
(c) Investigation into the combination effects of different track defects.
(d) Establishment of reliable quantitative relations between limiting values of track geometry parameters, track curvature and wheel force ratios.
(e) Study of a set of recommended values for track limiting value geometry defects that are defined as a function of degree of track curvature and track class.

For the above items, a detailed investigation by NUCARS is strongly suggested before proceeding with further field tests. This is recommended based on the following features and advantages of the NUCARS simulation approach:

- It is easy to isolate the effect of each surface geometrical parameter on the force ratio.
- Different car types can be simulated and compared on the same track conditions.
- Different car and lading types will react quite differently to the various types of limiting track geometry errors and speed (class of track) of operation.
- Combination effects of different track defects can be quickly designed, simulated and evaluated.
- Track and operation conditions like defect amplitudes, track curvature and car speed can be systematically changed.
- Field data of track surface variations from BC Rail main line tests or other available field tests can be included into the simulation if necessary.
- Cost efficiency.

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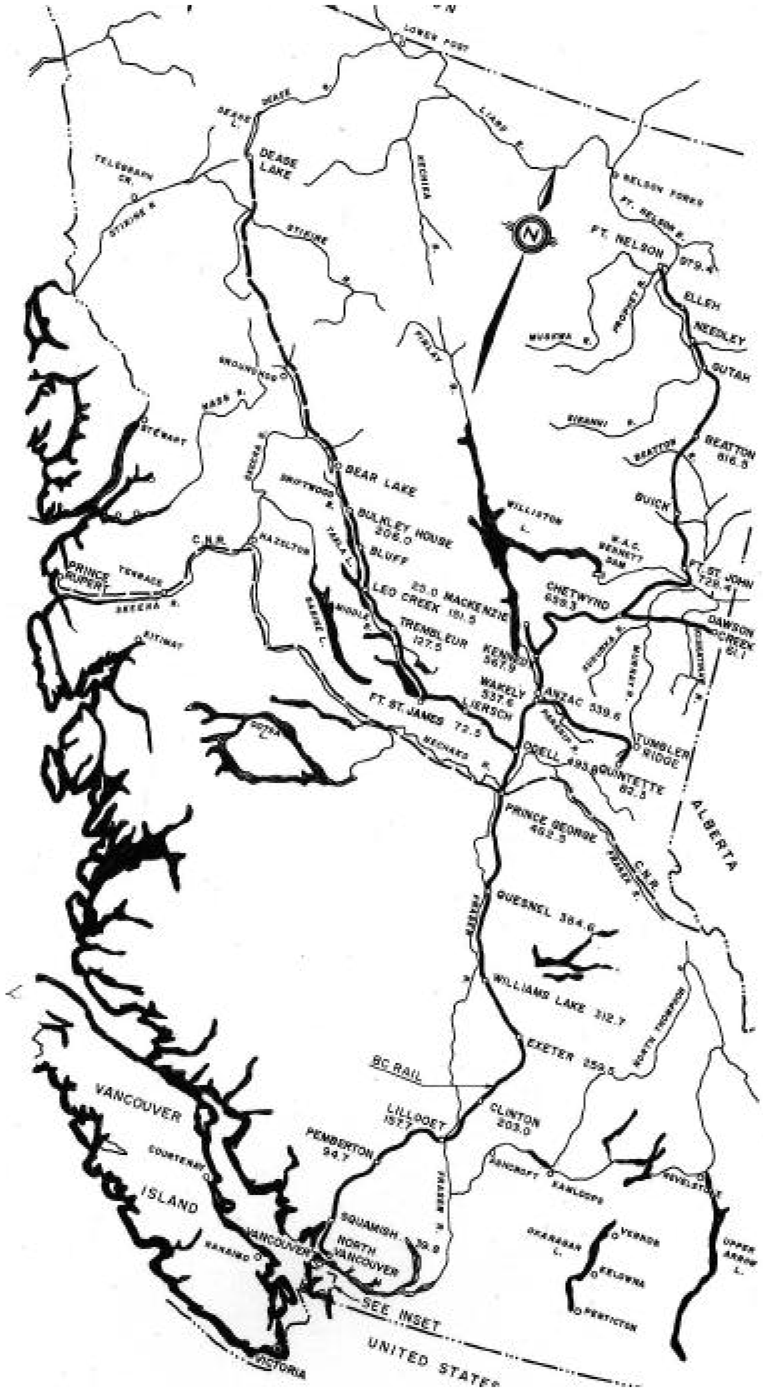

Figure 1 Field Test Route

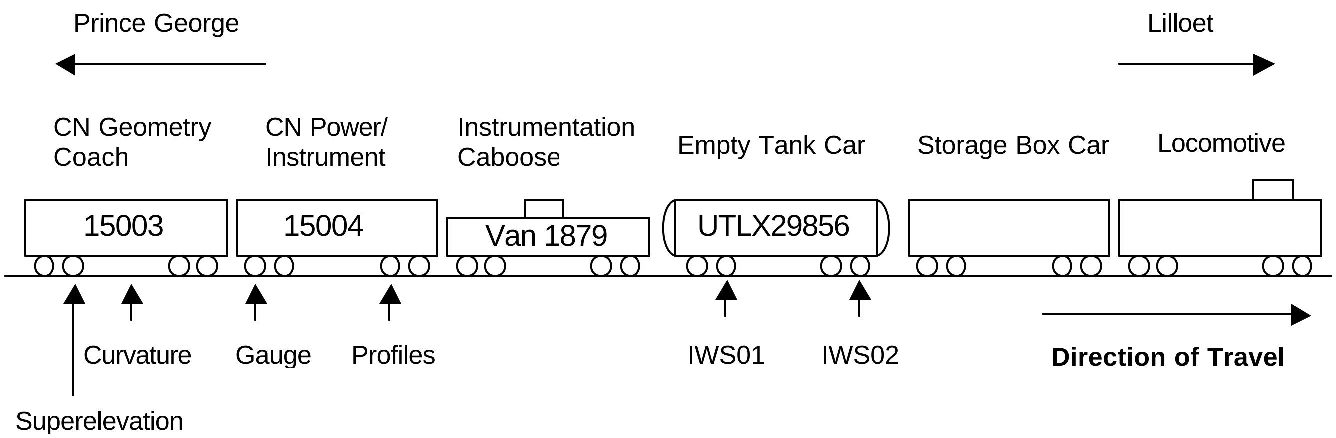

Figure 2 Test Train Consist and Locations of Major Measured Parameters

Table 1 Major Dimensions of Cars in Test Train Consist

Car Name	Car ID	Coupler to Coupler (inches)	Truckbase (inches)	Wheelbase (inches)
CN Geometry Coach	15003	1018.0	714.0	96.0
CN Power/Instrument Box Car	15004	791.0	555.0	72.0
Instrumentation Caboose	Van 1879	540.0	310.5	
Empty Tank Car	UTLX 29856	804.6	636.0	70.0

Table 2 Testsets of Field Data

Testset Number	Start Mile Post (mile)	Runing Mileage	End Mile Post (mile)
2	459.8	18.3	441.4
3	438.1	29.5	408.6
4	406.7	17.5	389.2
6	372.8	32.4	340.4
7	339.0	12.5	326.5
8	326.1	12.9	313.2
9	312.1	17.5	294.6
10	293.2	33.8	259.4
11	258.5	16.5	242.0
13	240.0	28.2	211.8
19	208.8	35.9	172.9
20	171.8	13.6	158.2
Total		268.8	

Table 3 Track Section Table (Part)

Dataset Number	Track Section Type	Measured Curvature Degree (Deg.)	Design Curve Degree (Deg.) *	Time at Beginning of Section (sec) **	Time at End of Section (sec)	Number of Data Points at Beginning of Section **	Number of Data Points at End of Section	Mileage at Section Beginning (Mile)	Mileage at End of Section (Mile)	Section Length (Feet)
2	Tangent			0.00	91.09	1	13664	459.75	458.74	5314
2	Spiral-entry			91.09	95.57	13665	14335	458.74	458.68	335
2	Curve body	-2.99	-3.17	95.57	97.34	14336	14602	458.68	458.65	133
2	Spiral-exit			97.34	100.89	14603	15133	458.65	458.60	265
2	Tangent			100.89	205.73	15134	30861	458.60	457.16	7624
2	Spiral-entry			205.73	210.01	30862	31501	457.16	457.10	307
2	Curve body	3.17	3.17	210.01	215.74	31502	32362	457.10	457.02	413
2	Spiral-exit			215.74	221.05	32363	33158	457.02	456.95	383
2	Tangent			221.05	227.93	33159	34191	456.95	456.86	499
2	Spiral-entry			227.93	229.91	34192	34487	456.86	456.83	142
2	Curve body	1.52	1.50	229.91	232.83	34488	34926	456.83	456.79	212
2	Spiral-exit			232.83	235.33	34927	35300	456.79	456.76	181
2	Tangent			235.33	266.91	35301	40038	456.76	456.31	2325
2	Spiral-entry			266.91	270.56	40039	40584	456.31	456.26	267
2	Curve body	-3.21	-3.33	270.56	284.63	40585	42696	456.26	456.07	1021
2	Spiral-exit			284.63	287.13	42697	43070	456.07	456.04	179
2	Tangent			287.13	296.61	43071	44493	456.04	455.91	685
…										
3	Tangent			174.83	231.33	26225	34701	436.66	436.20	2429
3	Spiral-entry			231.33	237.97	34702	35696	436.20	436.14	297
3	Curve body	8.47	8.33	237.97	239.26	35697	35890	436.14	436.13	58
3	Spiral			239.26	245.97	35891	36896	436.13	436.07	309
3	Curve body	-6.76	-7.33	251.21	253.14	37682	37972	436.02	436.01	91
3	Spiral			253.14	259.21	37973	38881	436.01	435.95	289
…										
11	Tangent			0.00	12.09	1	1814	258.50	258.44	309
11	Spiral-entry			12.09	20.62	1815	3093	258.44	258.40	214
11	Curve body	-7.93	-8.00	20.62	29.06	3094	4360	258.40	258.36	203
11	Spiral			29.06	33.19	4361	4978	258.36	258.34	96
11	Curve body	-5.91	-6.00	33.19	81.55	4979	12234	258.34	258.14	1091
11	Spiral-exit			81.55	94.35	12235	14153	258.14	258.09	244
11	Tangent			94.35	142.01	14154	21302	258.09	257.86	1198
11	Spiral-entry			142.01	149.83	21303	22475	257.86	257.81	267
11	Curve body	-5.92	-6.00	149.83	180.65	22476	27099	257.81	257.62	1047
11	Spiral-exit			180.65	190.37	27100	28556	257.62	257.55	327
11	Tangent			190.37	206.49	28557	30975	257.55	257.44	586
…										

* From BC Rail's Condensed Profile No. 4A , 1990

** Time was set to zero (point to 1) for each dataset

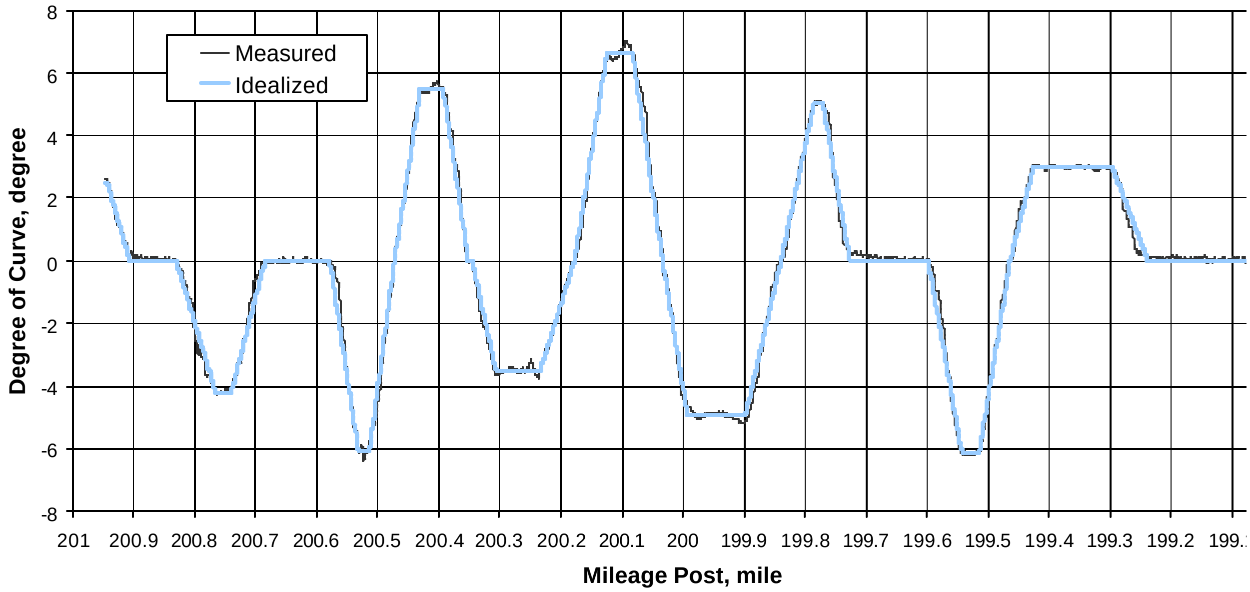

Figure 3 Track Curvature Comparison

Table 4 Geometry and Force Channels with Their Offset Distance from the Centre of Geometry Coach Car

Type	Parameter Name	Channel Name in Database Name	Parameter Unit	Offset Distance from Centre of Geometry Coach Car		
				metre	mile	Data Point
General	Test Train Speed	SPEED	mph	0	0	0
	Mileage	MILEAGE	mile	0	0	0
Geometry Parameters	Track Curvature	CURVAT	deg	0	0	0
	Left Profile 62	**LPROF62**	in	29.1338	0.018103	724
	Right Profile 62	**RPROF62**	in	29.1338	0.018103	724
	Cross Level	**XLEVEL**	in	29.1338	0.018103	724
	Superelevation	SUPEREL	in	0	0	0
	Warp31	**WARP31**	in	0	0	0
	Twist62	**TWIST62**	in	0	0	0
	Cant Deficiency	CANTDIF	in	0	0	0
	Track Gauge	GAGE_Box	in	13.0368	0.008101	324
Force Parameters	**Wheel L/V Lead Right**	**LV21**	1	65.9221	0.040962	1638
	Wheel L/V Lead Left	**LV22**	1	65.9221	0.040962	1638
	Wheel L/V Trail Right	**LV11**	1	49.7647	0.030922	1236
	Wheel L/V Trail Left	**LV12**	1	49.7647	0.030922	1236
	Axle Sum L/V Lead	**AX02LV**	1	65.9221	0.040962	1638
	Axle Sum L/V Trail	**AX01LV**	1	49.7647	0.030922	1236
	%Vforce Lead Right	**Q21%**	1	65.9221	0.040962	1638
	%Vforce Lead Left	**Q22%**	1	65.9221	0.040962	1638
	%Vforce Trail Right	**Q11%**	1	49.7647	0.030922	1236
	%Vforce Trail left	**Q12%**	1	49.7647	0.030922	1236
	Lforce Lead Right	Y21	kip	65.9221	0.040962	1638
	Lforce Lead Left	Y22	kip	65.9221	0.040962	1638
	Lforce Trail Right	Y11	kip	49.7647	0.030922	1236
	Lforce Trail Left	Y12	kip	49.7647	0.030922	1236
	Vforce Lead Right	Q21	kip	65.9221	0.040962	1638
	Vforce Lead Left	Q22	kip	65.9221	0.040962	1638
	Vforce Trail Right	Q11	kip	49.7647	0.030922	1236
	Vforce Trail left	Q12	kip	49.7647	0.030922	1236

Table 5 Number and Length of Different Track Sections

Section Type		Section Number		Length	
		Count	Percentage	Mileage	Percentage
Tangent		732	21.5%	125.1	46.5%
Curve	Curve Body	975	28.6%	68.2	25.4%
	Spiral	1700	49.9%	75.4	28.1%
Total		3407	100.0%	268.8	100.0%

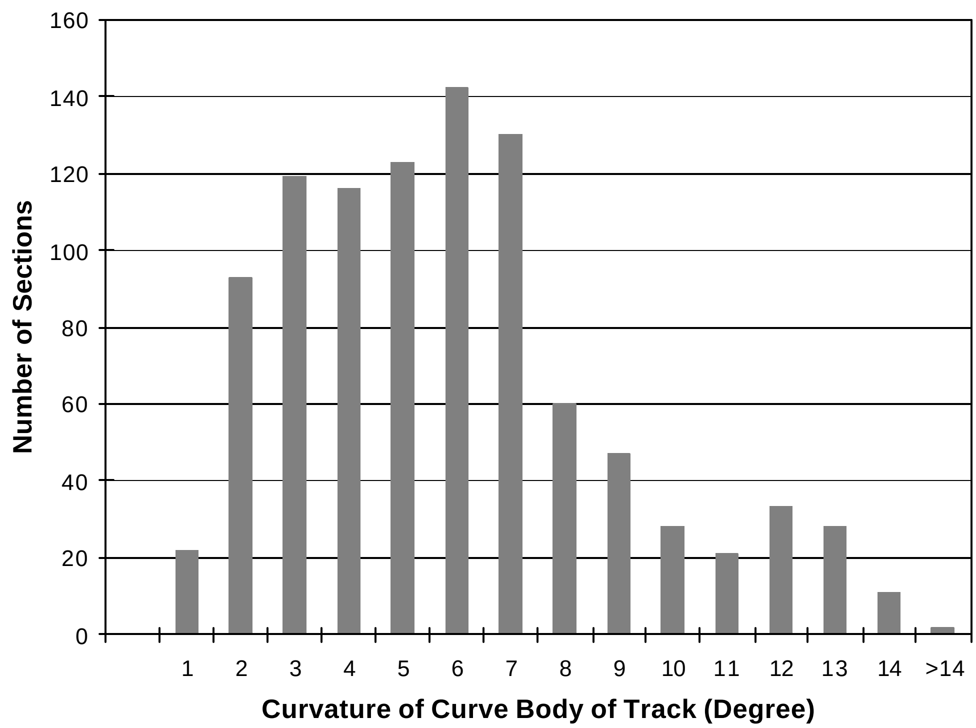

Figure 4 Degree Distribution of Track Curvature

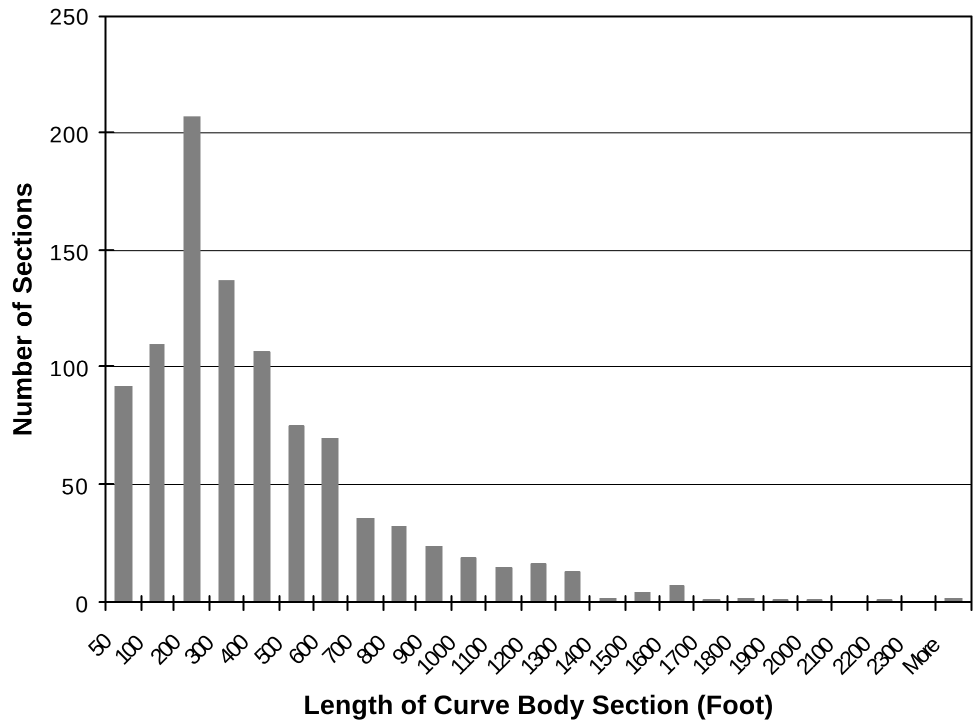

Figure 5 Length Distribution of Curve Body Sections

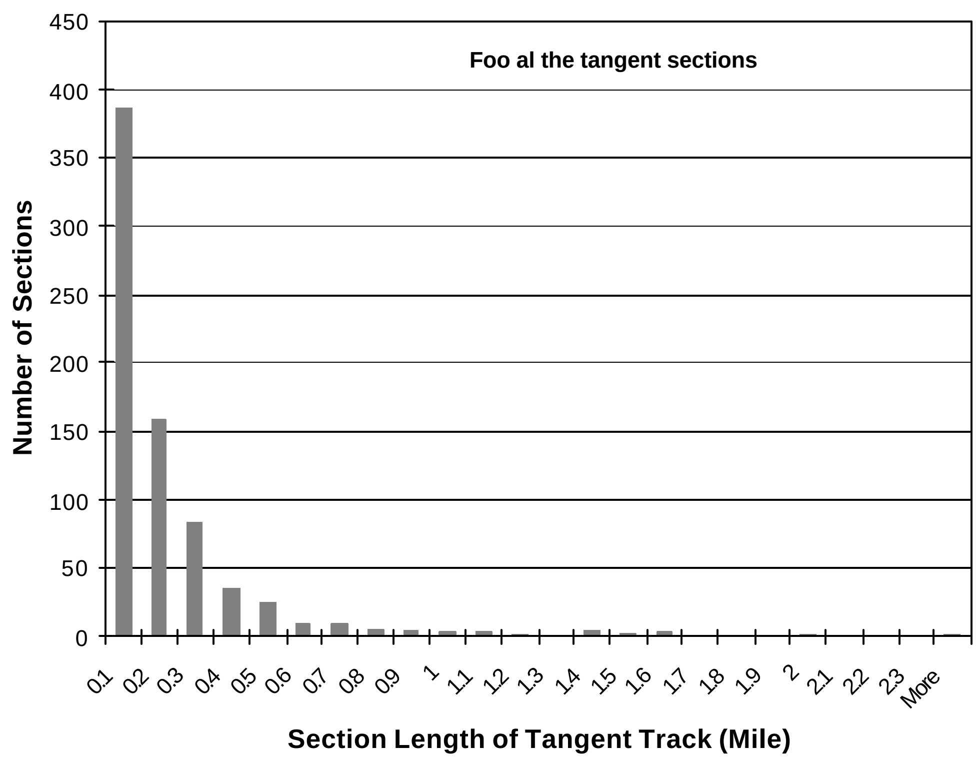

Figure 6 Length Distribution of Tangent Sections

Table 6 Track Safety Standards

Track Class			Cross Level (inch)			Profile (inch)		
Transport Canada Track Class	BC Province Track Class	BC Rail Maximum Allowable Speed	Transport Canada	BC Province	BC Rail Urgent	Transport Canada	BC Province	BC Rail Urgent
2	1	15 MPH	**2.000**	3.500	**2.500**	**2.750**	3.000	**2.500**
	2	20 MPH		2.500	**2.000**		2.500	**2.250**
	3	25 MPH		2.000	**1.750**		2.250	**2.000**
3		30 MPH	**1.750**		**1.750**	**2.250**		**1.875**
	4	35 MPH		1.750	**1.500**		2.000	**1.750**
		40 MPH			**1.500**			**1.625**
4	5	45 MPH	**1.250**	1.500	**1.250**	**2.000**	1.750	**1.375**
		50 MPH			**1.250**			**1.375**
	6	55 MPH		1.250	**1.250**		1.500	**1.250**
		60 MPH			**1.250**			**1.250**

Track Class			Warp31 (inch)			Twist62 (inch)				
							On Curves		On Tangents	
Transport Canada Track Class	BC Province Track Class	BC Rail Maximum Allowable Speed	Transport Canada	BC Province	BC Rail Urgent	Transport Canada*	BC Province	BC Rail Urgent	BC Province	BC Rail Urgent
2	1	15 MPH	**1.750**	2.000	**1.250**	**2.000**	2.500	**2.000**	3.000	3.000
	2	20 MPH		1.500	**1.250**		2.000	**1.750**	3.000	2.500
	3	25 MPH		1.250	**1.000**		2.000	**1.500**	2.500	2.500
3		30 MPH	**1.250**		**1.000**	**1.750**		**1.500**		2.500
	4	35 MPH		1.000	**0.750**		1.750	**1.500**	2.500	2.000
		40 MPH			**0.750**			**1.500**		2.000
4	5	45 MPH	**1.000**	0.750	**0.625**	**1.250**	1.750	**1.250**	2.000	1.500
		50 MPH			**0.625**			**1.250**		1.500
	6	55 MPH		0.625	**0.500**		1.500	**1.250**	1.750	1.500
		60 MPH			**0.500**			**1.250**		1.500

* The same value applies to both tangent and curve (body) tracks

Table 7 BC Rail Track Speed Limit

MPH RDC Units	Start Mileages	End Mileages	MPH Freight Units
40	462.4	460	30
55	460	454	50
45	454	451.5	30
55	451.5	449.5	50
55	449.5	444.5	40
35	444.5	444.2	25
55	444.2	442.5	40
40	442.5	442	30
55	442	439	40
50	439	429	30
30	429	428.5	20
50	428.5	420	30
55	420	414	40
55	414	408	30
35	408	405.5	25
50	405.5	401	35
35	401	400.5	20
50	400.5	397	35
35	397	380.8	20
35	380.8	380	20
45	380	377.4	30
45	377.4	377	30
65	377	375.9	50
55	375.9	375.2	50
55	375.2	373.7	50
65	373.7	371.2	50
55	371.2	367.7	50
65	367.7	367	50
50	367	355	35
55	355	343.2	35
40	343.2	343	30
45	343	333.6	35
40	333.6	333.3	25
40	333.3	326	30
35	326	325.5	25
45	325.5	321.6	30
40	321.6	319.8	30
30	319.8	318.8	20
45	318.8	317.3	35
45	317.3	315	35
35	315	312.9	25
50	312.9	296.6	30
55	296.6	295.3	35
40	295.3	294.3	25
55	294.3	291.8	35
40	291.8	291.5	25
55	291.5	260.2	35
55	260.2	259	35
40	259	242.7	25
55	242.7	211.9	35
30	211.9	211.5	20
55	211.5	206.1	35
35	206.1	205.9	30
55	205.9	191.4	35
35	191.4	160.4	20
30	160.4	160.1	20
35	160.1	157.8	20
35	157.8	157.6	20

Table 8 “Urgent” Twist62 Defects Scanned by Transport Canada’s Rules

Defect/ Track Type	Value of Twist62 Defect (inch)	Location of Twist62 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Track (degree)	Defect Number
Twist62 on Tangent Track	1.792	342.838	35		1
	1.919	259.288	35		2
	1.789	196.833	35		3
	2.047	191.478	35		4
	1.553	456.031	50		5
	1.453	449.882	50		6
	1.322	372.187	50		7
	1.565	367.796	50		8
Twist62 on Curve-Body Track	1.812	299.415	30	7.28	1
	1.912	399.943	35	1.72	2
	1.973	397.673	35	5.98	3
	2.687	339.815	35	8.58	4
	1.879	339.793	35	1.13	5
	1.798	338.281	35	6.49	6
	1.983	272.447	35	5.46	7
	1.410	456.245	50	3.21	8
	1.710	368.191	50	1.94	9
	1.388	367.858	50	1.88	10

Table 9 "Urgent" Warp31 Defects Scanned by Transport Canada's Rules

Track Type	Value of Warp31 Defect (inch)	Location of Warp31 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Related Curve Track (degree)	Defect Number
Warp31 on Spiral Track	1.313	452.396	30	5.18	1
	1.314	432.410	30	4.33	2
	1.250	423.771	30	2.78	3
	1.623	331.171	30	7.49	4
	1.325	324.788	30	5.11	5
	1.497	322.107	30	5.29	6
	1.336	312.865	30	4.82	7
	1.280	312.841	30	5.22	8
	1.275	306.308	30	6.07	9
	1.352	366.429	35	5.95	10
	1.320	351.157	35	2.68	11
	1.425	350.753	35	1.73	12
	1.271	348.503	35	1.52	13
	1.251	343.208	35	5.20	14
	1.658	339.813	35	8.58	15
	1.251	338.259	35	6.36	16
	1.258	337.736	35	6.58	17
	1.511	337.420	35	5.78	18
	1.310	334.121	35	3.96	19
	1.400	317.263	35	6.47	20
	1.495	291.952	35	5.97	21
	1.275	289.794	35	4.42	22
	1.404	281.919	35	4.11	23
	1.253	280.778	35	4.86	24
	1.378	272.697	35	5.77	25
	1.273	272.454	35	5.41	26
	1.286	272.392	35	5.51	27
	1.300	271.304	35	5.65	28
	1.374	267.985	35	7.01	29
	1.492	259.242	35	3.95	30
	1.370	191.485	35	4.68	31
	1.014	456.292	50	3.53	32
	1.411	368.284	50	2.14	33
	1.035	367.801	50	1.80	34

Table 10 “Priority” Twist62 Defects Scanned by BC Rail’s Urgent Limits

Defect/ Track Type	Value of Twist62 Defect (inch)	Location of Twist62 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Track (degree)	Defect Number
Twist62 on Tangent Track	1.846	166.665	20		1
	1.702	333.518	25		2
	1.705	329.909	30		3
	1.576	398.912	35		4
	1.792	342.838	35		5
	1.581	338.772	35		6
	1.533	338.250	35		7
	1.652	317.568	35		8
	1.671	280.365	35		9
	1.919	259.288	35		10
	1.540	242.201	35		11
	1.680	214.310	35		12
	1.789	196.833	35		13
	2.047	191.478	35		14
	1.554	416.432	40		15
	1.553	456.031	50		16
	1.453	449.882	50		17
	1.322	372.187	50		18
	1.565	367.796	50		19
Twist62 on Curve-Body Track	1.880	166.328	20	13.47	1
	1.825	159.985	20	14.22	2
	1.579	314.797	25	6.00	3
	1.554	255.855	25	3.83	4
	1.682	413.163	30	7.10	5
	1.679	332.424	30	7.26	6
	1.594	330.846	30	4.79	7
	1.588	329.987	30	8.16	8
	1.553	324.932	30	7.51	9
	1.708	320.822	30	7.87	10
	1.812	299.415	30	7.28	11
	1.912	399.943	35	1.72	12
	1.973	397.673	35	5.98	13
	2.687	339.815	35	8.58	14
	1.879	339.793	35	1.13	15
	1.798	338.281	35	6.49	16
	1.511	337.411	35	5.96	17
	1.552	335.201	35	6.14	18
	1.627	318.223	35	7.22	19
	1.521	289.855	35	4.50	20
	1.585	287.411	35	1.93	21
	1.701	274.819	35	5.55	22
	1.983	272.447	35	5.46	23
	1.611	272.336	35	6.44	24
	1.532	271.990	35	4.51	25
	1.633	271.676	35	3.55	26
	1.554	268.741	35	3.13	27
	1.646	267.607	35	3.44	28
	1.410	456.245	50	3.21	29
	1.710	368.191	50	1.94	30
	1.388	367.858	50	1.88	31

Table 11 “Priority” Warp31 Defects Scanned by BC Rail’s Urgent Limits

Defect Number	Value of Warp31 Defect (inch)	Location of Warp31 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Related Curve Track (degree)	Defect Number	Value of Warp31 Defect (inch)	Location of Warp31 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Related Curve Track (degree)	Defect Number	Value of Warp31 Defect (inch)	Location of Warp31 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Related Curve Track (degree)
1	1.311	190.422	20	11.07	67	0.846	403.792	35	5.75	133	1.210	339.747	35	3.94
2	1.317	190.215	20	11.90	68	0.870	403.749	35	6.26	134	0.891	338.848	35	3.35
3	1.345	188.439	20	11.73	69	0.988	403.543	35	6.10	135	0.794	338.775	35	3.40
4	1.370	184.169	20	8.62	70	1.000	403.385	35	4.81	136	0.933	338.636	35	4.04
5	1.289	173.576	20	3.10	71	0.951	403.163	35	4.67	137	0.804	338.568	35	3.35
6	1.300	166.720	20	14.08	72	0.912	402.955	35	6.13	138	0.882	338.292	35	6.42
7	1.521	159.988	20	14.86	73	0.921	402.802	35	6.09	139	1.251	338.259	35	6.36
8	1.027	444.346	25	6.01	74	0.787	401.767	35	6.77	140	1.008	338.210	35	5.78
9	1.001	406.359	25	6.72	75	1.130	401.498	35	5.78	141	0.967	338.109	35	5.68
10	1.128	406.289	25	10.25	76	1.249	399.909	35	1.78	142	0.945	337.999	35	5.12
11	1.471	406.196	25	10.37	77	0.878	399.402	35	5.23	143	0.994	337.947	35	5.06
12	1.056	333.520	25	5.25	78	0.823	399.292	35	4.04	144	0.923	337.827	35	5.75
13	1.211	325.976	25	9.69	79	0.802	397.737	35	6.42	145	1.258	337.736	35	6.58
14	1.251	314.931	25	9.42	80	0.944	397.520	35	5.67	146	0.857	337.494	35	6.96
15	1.098	295.235	25	5.03	81	0.904	366.998	35	4.18	147	1.511	337.420	35	5.78
16	1.117	294.619	25	5.79	82	1.112	366.757	35	3.78	148	1.128	337.334	35	6.08
17	1.001	256.747	25	1.18	83	1.352	366.429	35	5.95	149	0.831	337.263	35	5.65
18	1.097	255.916	25	3.55	84	0.940	366.193	35	6.03	150	1.135	337.202	35	5.72
19	1.157	254.237	25	2.70	85	1.234	366.074	35	6.44	151	0.771	336.905	35	6.02
20	1.041	251.984	25	6.37	86	0.922	365.547	35	5.89	152	0.895	336.770	35	6.04
21	1.064	251.865	25	6.23	87	0.972	361.212	35	3.97	153	0.995	336.068	35	5.24
22	1.153	453.061	30	6.02	88	0.815	361.033	35	4.16	154	1.088	336.010	35	5.19
23	1.313	452.396	30	5.18	89	0.964	360.929	35	5.94	155	0.882	335.783	35	5.54
24	1.091	452.058	30	3.71	90	1.160	360.816	35	5.83	156	1.163	335.694	35	5.66
25	1.082	451.555	30	2.91	91	1.072	359.926	35	6.09	157	1.119	335.476	35	6.25
26	1.010	442.279	30	6.10	92	0.804	359.303	35	1.07	158	0.901	335.370	35	6.24
27	1.049	436.091	30	8.37	93	0.830	358.697	35	6.62	159	0.971	335.207	35	6.30
28	1.314	432.410	30	4.33	94	1.004	358.594	35	6.59	160	1.219	335.071	35	6.40
29	1.000	427.318	30	8.04	95	1.210	357.964	35	4.83	161	1.226	334.952	35	5.64
30	1.250	423.771	30	2.78	96	0.809	355.300	35	3.48	162	0.824	334.692	35	5.84
31	1.048	420.186	30	8.35	97	0.897	355.064	35	4.06	163	0.996	334.579	35	6.15
32	1.121	413.217	30	7.32	98	0.809	352.716	35	1.86	164	1.084	334.447	35	6.00
33	1.190	409.794	30	7.67	99	1.064	352.200	35	6.64	165	1.310	334.121	35	3.96
34	1.246	333.173	30	6.17	100	1.044	352.157	35	6.70	166	0.886	334.050	35	4.09
35	1.248	332.567	30	8.10	101	1.232	351.865	35	4.72	167	0.758	333.627	35	4.09
36	1.127	332.199	30	8.25	102	0.831	351.273	35	2.74	168	0.911	318.352	35	7.03
37	1.156	331.455	30	7.70	103	1.320	351.157	35	2.68	169	0.761	318.302	35	6.63
38	1.623	331.171	30	7.49	104	1.074	350.856	35	4.44	170	0.832	318.160	35	7.14
39	1.050	330.158	30	7.98	105	0.770	350.801	35	1.65	171	0.874	317.888	35	4.33
40	1.064	329.932	30	8.76	106	1.425	350.753	35	1.73	172	1.017	317.826	35	4.20
41	1.154	329.165	30	7.81	107	0.756	350.496	35	2.20	173	0.873	317.646	35	4.57
42	1.174	328.492	30	7.95	108	0.914	350.017	35	5.53	174	0.964	317.569	35	4.41
43	1.192	328.290	30	6.67	109	1.089	349.933	35	5.42	175	1.111	317.377	35	6.35
44	1.140	325.051	30	6.84	110	1.236	348.881	35	3.95	176	1.400	317.263	35	6.47
45	1.035	324.973	30	6.93	111	1.271	348.503	35	1.52	177	1.002	317.205	35	5.78
46	1.011	324.888	30	6.97	112	0.915	348.224	35	4.13	178	1.152	317.110	35	5.57
47	1.325	324.788	30	5.11	113	0.782	347.925	35	4.36	179	1.207	316.039	35	4.68
48	1.026	324.677	30	5.26	114	0.836	347.766	35	3.60	180	0.895	315.868	35	5.03
49	1.012	323.881	30	7.34	115	0.780	347.675	35	3.43	181	0.868	315.373	35	4.44
50	1.497	322.107	30	5.29	116	0.950	347.473	35	2.75	182	1.231	315.304	35	3.98
51	1.022	321.548	30	7.11	117	1.083	347.211	35	3.91	183	0.840	315.034	35	4.15
52	1.068	321.450	30	7.15	118	0.861	346.861	35	4.22	184	0.981	315.008	35	8.11
53	1.132	320.827	30	7.55	119	0.770	346.742	35	4.33	185	0.864	296.458	35	8.61
54	1.336	312.865	30	4.82	120	0.862	344.119	35	4.33	186	0.944	296.337	35	5.81
55	1.280	312.841	30	5.22	121	0.860	344.050	35	4.22	187	0.802	296.283	35	5.93
56	1.171	309.151	30	7.36	122	0.780	343.382	35	5.09	188	0.780	295.953	35	3.76
57	1.081	307.342	30	5.99	123	1.251	343.208	35	5.20	189	0.870	295.579	35	5.10
58	1.207	306.509	30	7.62	124	1.135	342.929	35	2.63	190	1.188	295.430	35	4.96
59	1.041	306.337	30	7.94	125	1.080	342.841	35	2.80	191	0.888	293.012	35	4.50
60	1.275	306.308	30	6.07	126	0.866	341.283	35	1.38	192	0.810	292.872	35	2.82
61	1.038	304.566	30	4.47	127	0.791	341.087	35	2.99	193	1.030	292.797	35	3.60
62	1.055	303.524	30	4.90	128	1.036	340.392	35	5.57	194	0.832	292.671	35	0.80
63	0.877	405.395	35	6.93	129	0.811	340.184	35	5.82	195	0.976	292.087	35	3.79
64	1.035	405.199	35	6.90	130	0.806	340.042	35	4.13	196	1.495	291.952	35	5.97
65	1.235	404.836	35	3.82	131	1.169	339.848	35	3.03	197	1.057	290.700	35	5.56
66	0.946	404.740	35	5.02	132	1.658	339.813	35	8.58	198	1.011	290.578	35	5.71

Defect Number	Value of Warp31 Defect (inch)	Location of Warp31 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Related Curve Track (degree)
199	1.060	290.261	35	5.64
200	1.205	290.136	35	5.75
201	0.966	289.920	35	6.32
202	1.275	289.794	35	4.42
203	1.213	289.652	35	5.82
204	1.090	289.497	35	5.64
205	0.783	289.229	35	4.63
206	0.756	288.857	35	4.14
207	1.085	288.694	35	5.70
208	0.811	286.990	35	3.44
209	0.891	286.767	35	6.77
210	1.057	286.454	35	5.71
211	0.893	286.374	35	5.69
212	0.800	285.552	35	6.00
213	0.821	284.201	35	6.05
214	1.075	283.979	35	6.09
215	0.924	283.764	35	5.54
216	0.870	283.306	35	3.57
217	0.901	282.897	35	2.79
218	0.928	282.239	35	5.81
219	1.087	282.108	35	6.09
220	1.404	281.919	35	4.11
221	0.859	281.826	35	4.02
222	0.810	280.893	35	5.01
223	1.253	280.778	35	4.86
224	0.755	280.129	35	2.98
225	0.872	279.858	35	4.85
226	1.061	278.679	35	3.72
227	0.907	278.607	35	3.54
228	0.752	278.549	35	3.75
229	0.808	277.912	35	5.95
230	1.040	277.713	35	5.86
231	0.781	277.391	35	5.97
232	0.905	277.293	35	5.49
233	0.997	276.973	35	5.41
234	0.842	276.686	35	4.27
235	1.124	276.632	35	4.32
236	0.854	275.838	35	5.84
237	0.934	275.724	35	5.98
238	1.096	275.560	35	4.79
239	0.882	275.200	35	4.23
240	0.913	275.152	35	5.87
241	0.843	275.055	35	6.20
242	0.911	274.907	35	6.26
243	0.854	274.672	35	5.39
244	0.817	274.363	35	4.29
245	0.929	274.224	35	3.88
246	1.012	273.737	35	3.24
247	0.804	273.692	35	3.23
248	0.809	273.543	35	6.21
249	1.378	272.697	35	5.77
250	0.987	272.532	35	6.31
251	1.273	272.454	35	5.41
252	1.286	272.392	35	5.51
253	0.945	272.336	35	6.38
254	0.976	272.281	35	6.38
255	0.860	271.992	35	4.65
256	1.006	271.934	35	4.29
257	0.967	271.794	35	6.63
258	1.213	271.743	35	6.38
259	0.816	271.637	35	3.42
260	0.920	271.468	35	7.05
261	0.893	271.400	35	6.98
262	1.300	271.304	35	5.65
263	0.917	271.215	35	5.57
264	0.800	271.136	35	2.98

Defect Number	Value of Warp31 Defect (inch)	Location of Warp31 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Related Curve Track (degree)
265	0.802	270.524	35	3.82
266	0.909	270.393	35	2.68
267	1.013	269.958	35	5.00
268	0.863	269.604	35	6.44
269	0.912	269.493	35	6.52
270	1.031	269.210	35	6.14
271	1.010	269.094	35	5.78
272	0.846	268.912	35	4.10
273	0.912	268.747	35	3.06
274	0.845	268.694	35	3.06
275	0.834	268.184	35	5.41
276	0.759	268.105	35	5.32
277	1.374	267.985	35	7.01
278	0.796	267.898	35	5.35
279	0.938	267.801	35	5.09
280	0.912	267.748	35	6.17
281	0.890	267.642	35	6.15
282	0.841	267.555	35	3.39
283	0.808	267.334	35	1.48
284	0.842	267.000	35	5.95
285	1.001	266.837	35	6.03
286	0.987	266.557	35	3.93
287	0.766	266.036	35	4.23
288	0.972	265.961	35	4.25
289	0.897	265.593	35	2.95
290	0.925	265.002	35	5.67
291	1.087	264.819	35	6.06
292	1.018	264.439	35	5.85
293	0.887	264.101	35	3.00
294	0.889	263.676	35	5.20
295	0.948	263.618	35	5.08
296	0.984	263.396	35	6.14
297	0.872	263.233	35	6.30
298	0.837	263.051	35	6.00
299	0.854	261.884	35	4.93
300	0.803	261.413	35	4.36
301	0.863	259.729	35	4.72
302	1.107	259.294	35	2.64
303	1.492	259.242	35	3.95
304	1.009	242.221	35	4.24
305	1.005	242.014	35	3.06
306	0.761	237.342	35	5.95
307	0.774	230.074	35	5.98
308	0.836	229.927	35	5.97
309	0.750	229.319	35	6.29
310	0.807	228.931	35	6.09
311	0.825	228.714	35	5.98
312	0.979	228.246	35	6.01
313	0.783	227.511	35	6.06
314	0.767	226.759	35	6.67
315	0.849	226.652	35	6.57
316	0.830	226.502	35	5.71
317	0.829	224.833	35	6.22
318	0.822	224.687	35	6.56
319	0.931	222.086	35	6.18
320	0.911	219.758	35	6.44
321	0.839	214.986	35	6.33
322	0.855	214.381	35	6.17
323	0.916	214.316	35	6.22
324	0.863	213.966	35	6.22
325	1.185	212.582	35	3.91
326	0.960	208.659	35	6.10
327	0.769	207.583	35	5.94
328	0.777	206.621	35	5.87
329	0.782	205.781	35	5.80
330	0.772	205.640	35	7.32

Defect Number	Value of Warp31 Defect (inch)	Location of Warp31 Defect (mile)	Track Class in Speed Limit (mph)	Curvature of Related Curve Track (degree)
331	0.883	205.277	35	5.91
332	0.817	205.178	35	3.28
333	0.861	205.052	35	5.62
334	0.791	204.800	35	5.51
335	0.755	204.178	35	5.45
336	0.822	203.434	35	6.10
337	0.849	202.610	35	6.11
338	1.018	202.567	35	6.06
339	1.002	202.092	35	5.81
340	0.759	201.718	35	5.97
341	0.949	201.510	35	6.13
342	0.989	200.793	35	4.18
343	0.998	200.489	35	5.84
344	0.810	200.356	35	5.58
345	1.011	200.048	35	6.71
346	0.867	199.859	35	5.14
347	0.979	199.477	35	6.12
348	0.961	198.566	35	5.98
349	0.790	198.058	35	6.31
350	0.989	197.905	35	6.69
351	1.109	196.842	35	5.86
352	0.776	196.798	35	6.22
353	1.033	196.610	35	6.29
354	0.975	194.281	35	5.21
355	1.165	194.168	35	5.04
356	0.972	193.152	35	4.65
357	1.071	191.554	35	4.75
358	1.370	191.485	35	4.68
359	1.028	191.426	35	6.06
360	0.751	446.973	40	2.85
361	0.767	446.418	40	1.85
362	0.781	445.887	40	3.83
363	0.793	445.570	40	2.09
364	0.771	445.036	40	2.50
365	0.923	444.968	40	3.06
366	0.856	444.832	40	3.83
367	1.020	444.799	40	4.05
368	0.924	444.640	40	4.34
369	0.937	443.448	40	2.87
370	0.800	441.970	40	8.28
371	0.887	441.680	40	4.17
372	0.760	441.615	40	4.51
373	0.861	419.871	40	6.51
374	0.783	418.154	40	3.97
375	0.889	417.295	40	2.79
376	0.698	458.709	50	2.97
377	0.674	458.627	50	2.93
378	0.793	457.120	50	2.97
379	0.921	456.989	50	3.26
380	0.645	456.762	50	1.40
381	1.014	456.292	50	3.53
382	0.899	456.051	50	3.23
383	0.893	455.870	50	1.82
384	0.818	454.178	50	3.99
385	0.922	451.432	50	2.65
386	0.696	372.366	50	2.02
387	0.832	372.193	50	1.99
388	0.642	372.042	50	2.07
389	0.660	369.798	50	1.97
390	0.996	369.629	50	2.04
391	1.411	368.284	50	2.14
392	0.713	368.106	50	2.01
393	0.775	367.894	50	1.97
394	1.035	367.801	50	1.80
395	0.987	367.586	50	3.05
396	0.776	367.313	50	3.20

Table 12 "Urgent" Force Defects Scanned by AAR Chapter 11 Rules

Track Type	Force Defect Name	Defect Value	Defect Location (mile)	Degree of Curve Track	Number
Tangent Track	Wheel L/V Ratio	0.995	311.351		1
Curve Track	Axle Sum L/V Ratio	1.510	428.556	13.71	2
	Wheel L/V Ratio	1.085	390.671	6.34	3
	Wheel L/V Ratio	0.999	365.585	5.94	4
	Retained Vertical Force (%)	8.7%	291.943	5.99	5
	Wheel L/V Ratio	0.991	259.340	1.66	6
	Axle Sum L/V Ratio	1.503	205.633	6.91	7
Spiral Track	Wheel L/V Ratio	1.230	319.578	7.90	8

Table 13 "Priority" Force Defects Scanned by 80% AAR Chapter 11 Rules

Track Type	Force Defect Name	Defect Value	Defect Location (mile)	Degree of Curve Track	Number
Tangent Track	Retained Vertical Force (%)	25.6%	424.386		1
	Retained Vertical Force (%)	11.3%	408.973		2
	Retained Vertical Force (%)	23.5%	398.921		3
	Wheel L/V Ratio	0.995	311.351		4
	Retained Vertical Force (%)	27.0%	242.207		5
	Wheel L/V Ratio	0.840	193.047		6
	Wheel L/V Ratio	0.827	180.586		7
	Retained Vertical Force (%)	26.0%	165.155		8
Curve Track	Axle Sum L/V Ratio	1.510	428.556	13.71	1
	Retained Vertical Force (%)	27.9%	406.225	10.20	2
	Wheel L/V Ratio	0.941	397.678	5.98	3
	Retained Vertical Force (%)	26.1%	396.660	4.05	4
	Wheel L/V Ratio	1.085	390.671	6.34	5
	Axle Sum L/V Ratio	1.242	366.334	5.72	6
	Axle Sum L/V Ratio	1.203	366.318	5.68	7
	Axle Sum L/V Ratio	1.215	366.124	6.16	8
	Wheel L/V Ratio	0.999	365.585	5.94	9
	Axle Sum L/V Ratio	1.205	359.843	5.85	10
	Axle Sum L/V Ratio	1.265	349.974	5.39	11
	Wheel L/V Ratio	0.921	349.953	5.39	12
	Retained Vertical Force (%)	24.2%	332.260	8.16	13
	Wheel L/V Ratio	0.853	330.015	8.16	14
	Axle Sum L/V Ratio	1.259	320.804	7.87	15
	Axle Sum L/V Ratio	1.270	318.923	8.00	16
	Retained Vertical Force (%)	8.7%	291.943	5.99	17
	Wheel L/V Ratio	0.991	259.340	1.66	18
	Retained Vertical Force (%)	27.5%	256.868	2.60	19
	Axle Sum L/V Ratio	1.363	252.713	4.86	20
	Axle Sum L/V Ratio	1.219	247.705	4.41	21
	Axle Sum L/V Ratio	1.209	239.853	3.95	22
	Axle Sum L/V Ratio	1.224	231.669	6.92	23
	Axle Sum L/V Ratio	1.215	206.144	5.41	24
	Axle Sum L/V Ratio	1.231	206.113	5.41	25
	Axle Sum L/V Ratio	1.201	206.000	5.41	26
	Axle Sum L/V Ratio	1.250	205.866	5.41	27
	Axle Sum L/V Ratio	1.503	205.633	6.91	28
	Axle Sum L/V Ratio	1.201	205.604	6.91	29
	Axle Sum L/V Ratio	1.260	203.526	6.19	30
	Axle Sum L/V Ratio	1.314	202.135	5.89	31
	Axle Sum L/V Ratio	1.251	201.641	6.05	32
	Axle Sum L/V Ratio	1.218	201.603	6.05	33
	Axle Sum L/V Ratio	1.256	185.687	12.94	34
	Axle Sum L/V Ratio	1.212	185.644	12.94	35
	Axle Sum L/V Ratio	1.310	185.293	11.84	36
	Axle Sum L/V Ratio	1.268	185.242	11.84	37
	Axle Sum L/V Ratio	1.241	184.858	12.17	38
	Axle Sum L/V Ratio	1.247	184.842	12.17	39
Spiral Track	Wheel L/V Ratio	0.851	453.072	6.02	1
	Wheel L/V Ratio	0.885	444.803	4.05	2
	Axle Sum L/V Ratio	1.244	360.819	5.83	3
	Axle Sum L/V Ratio	1.202	358.677	6.62	4
	Retained Vertical Force (%)	18.4%	334.445	6.00	5
	Wheel L/V Ratio	1.230	319.578	7.90	6
	Retained Vertical Force (%)	23.6%	317.833	4.20	7
	Retained Vertical Force (%)	27.2%	288.693	5.70	8
	Wheel L/V Ratio	0.803	255.915	3.55	9
	Axle Sum L/V Ratio	1.224	252.665	4.93	10
	Axle Sum L/V Ratio	1.338	205.804	5.80	11
	Axle Sum L/V Ratio	1.362	203.451	6.10	12
	Axle Sum L/V Ratio	1.280	202.571	6.06	13
	Axle Sum L/V Ratio	1.236	202.342	6.11	14
	%Vforce Lead Right	23.0%	191.485	4.63	15
	%Vforce Trail Right	25.9%	190.320	11.68	16
	Wheel L/V Ratio	0.866	189.494	5.78	17
	Wheel L/V Ratio	0.893	188.652	7.24	18
	Axle Sum L/V Ratio	1.240	186.495	11.69	19
	Axle Sum L/V Ratio	1.263	186.297	11.31	20
	Axle Sum L/V Ratio	1.255	185.194	11.75	21
	Retained Vertical Force (%)	24.4%	173.553	3.10	22
	Wheel L/V Ratio	0.800	173.516	7.72	23

Table 14 Number Comparison of "Urgent" Geometry and Force Defects

Track Type	"Urgent" Geometry Defects			"Urgent" Force Defects			
	Twist62	Warp31	**Total**	Wheel L/V	Axle Sum L/V	Retained Vertical Force	**Total**
Tangent	8		**8**	1			**1**
Curve	10		**10**	3	2	1	**6**
Spiral		34	**34**	1			**1**

Table 15 Number Comparison of "Priority" Geometry and Force Defects

Track Type	"Priority" Geometry Defects			"Priority" Force Defects			
	Twist62	Warp31	**Total**	Wheel L/V	Axle Sum L/V	Retained Vertical Force	**Total**
Tangent	19		**19**	3		5	**8**
Curve	31		**31**	6	28	5	**39**
Spiral		396	**396**	7	10	6	**23**

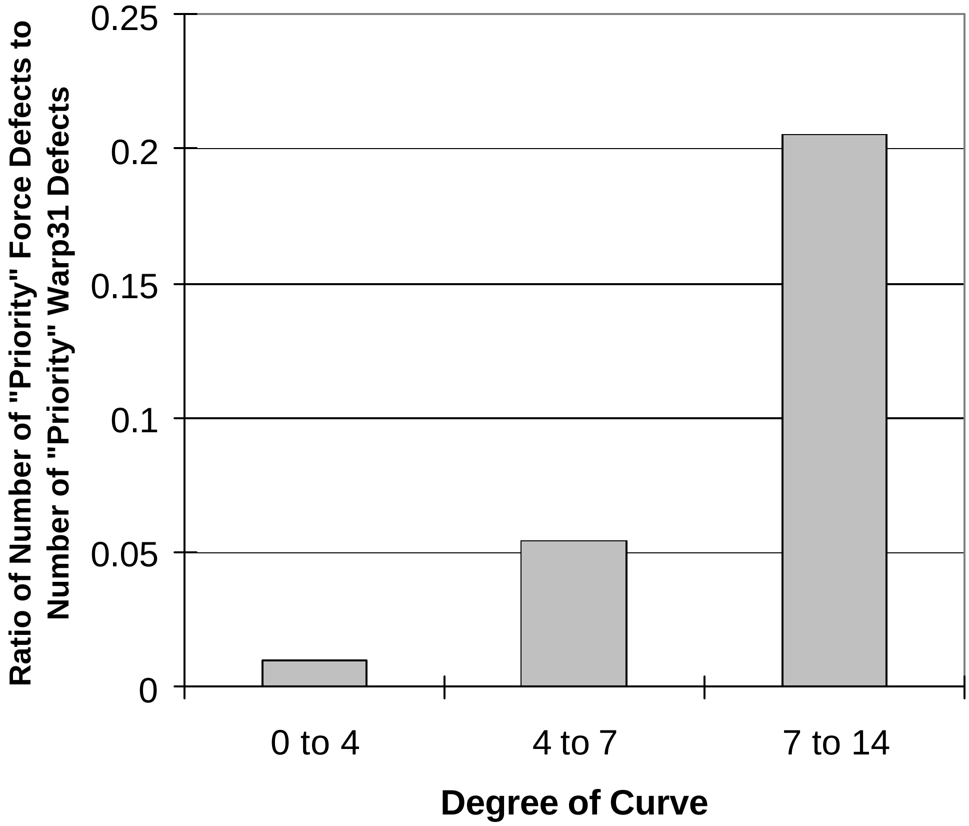

Figure 7 Effects of Curvature on Force Defect Number per Warp31 Defect

Table 16 Geometry Defects Corresponding with Force Defects at "Priority" Level

Geometry Defect				Force Defect			(Train Speed) / (Track Speed Limit)	Cant Deficiency (inch)
Geometry Defect	Value of Geometry Defect (inch)	Curvature of Track (degree)	Location of Geometry Defect (mile)	Location of Force Defect (mile)	Force Defect	Value of Force Defect		
Warp31 on Spirals	1.020	4.05	444.799	444.803	Wheel L/V Ratio	0.885	0.856	1.861
	1.160	5.83	360.816	360.819	Axle Sum L/V Ratio	1.244	0.998	1.862
	0.830	6.62	358.697	358.677	Axle Sum L/V Ratio	1.202	1.104	1.982
	1.084	6.00	334.447	334.445	Retained Vertical Force (%)	18.4%	0.802	2.747
	1.017	4.20	317.826	317.833	Retained Vertical Force (%)	23.6%	0.796	1.642
	1.495	**5.97**	**291.952**	**291.943**	**Retained Vertical Force (%)**	**8.7%**	**0.933**	**3.715**
	1.097	3.55	255.916	255.915	Wheel L/V Ratio	0.803	1.370	1.233
	0.772	7.32	205.640	205.604	Axle Sum L/V Ratio	1.201	0.512	2.854
	1.018	6.06	202.567	202.571	Axle Sum L/V Ratio	1.280	0.560	2.437
	1.370	4.63	-191.485	191.485	Retained Vertical Force (%)	23.0%	0.609	1.441
	1.289	3.10	-173.576	173.553	Retained Vertical Force (%)	24.4%	1.000	1.246
Twist62 on Curves	1.973	5.98	397.673	397.678	Wheel L/V Ratio	0.941	0.468	3.711
	1.708	7.87	320.822	320.804	Axle Sum L/V Ratio	1.259	1.118	2.781

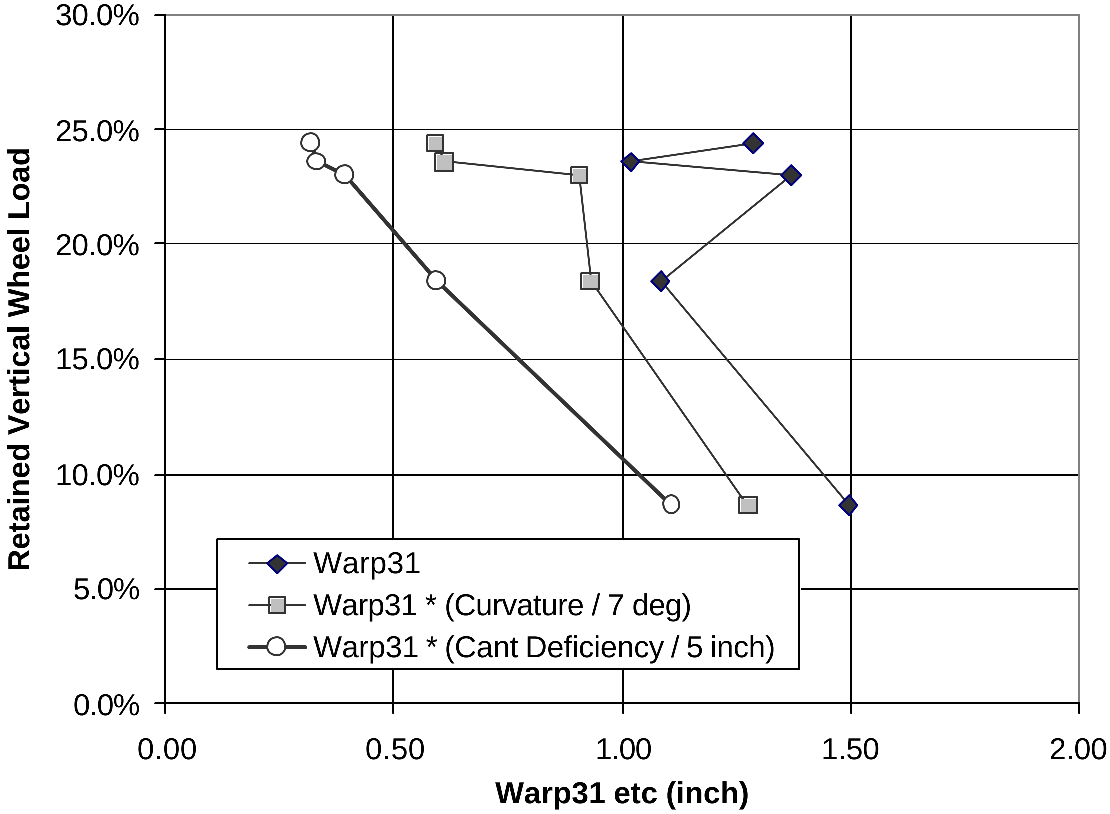

Figure 8 Relation between Retained Vertical Force and Warp31

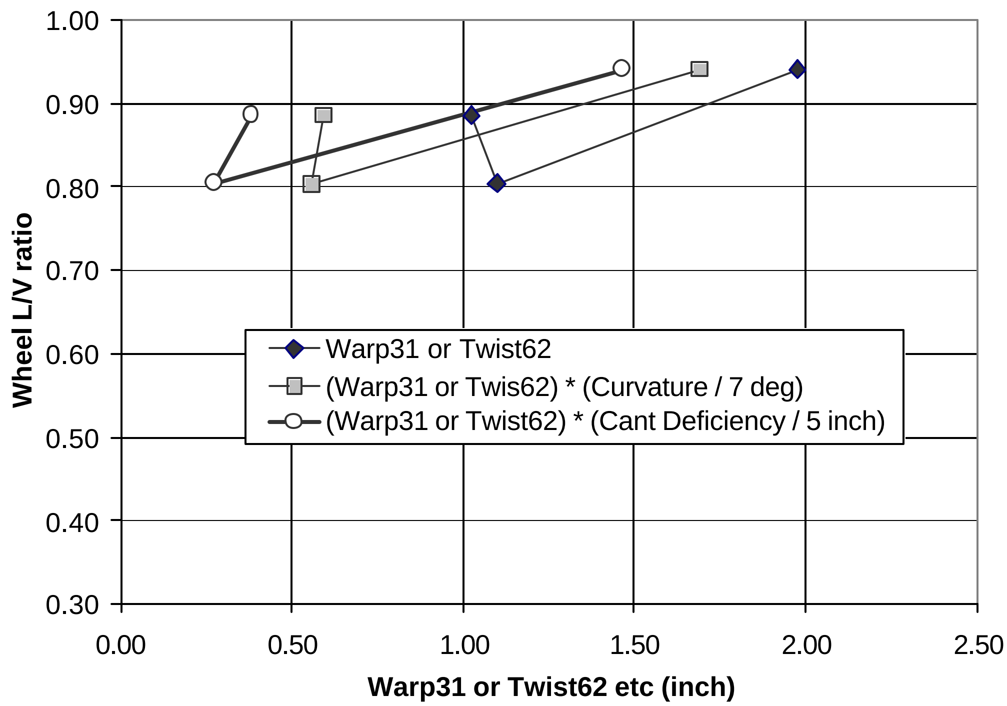

Figure 9 Relation between Wheel L/V Ratio and Warp31 or Twist62

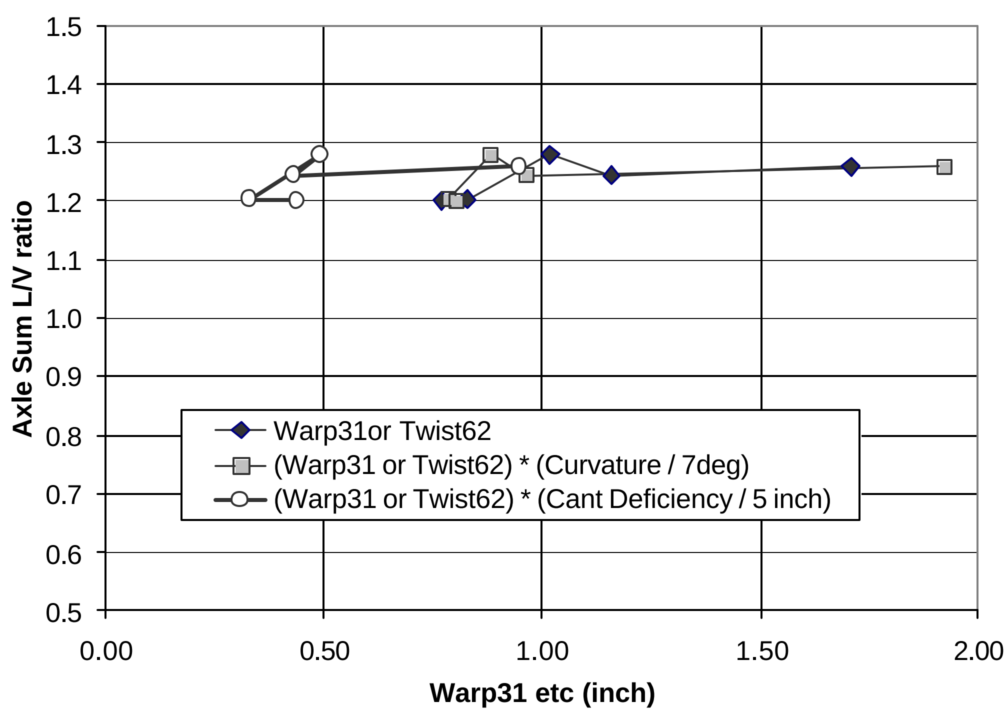

Figure 10 Relation between Axle Sum L/V Ratio and Warp31 or Twist62

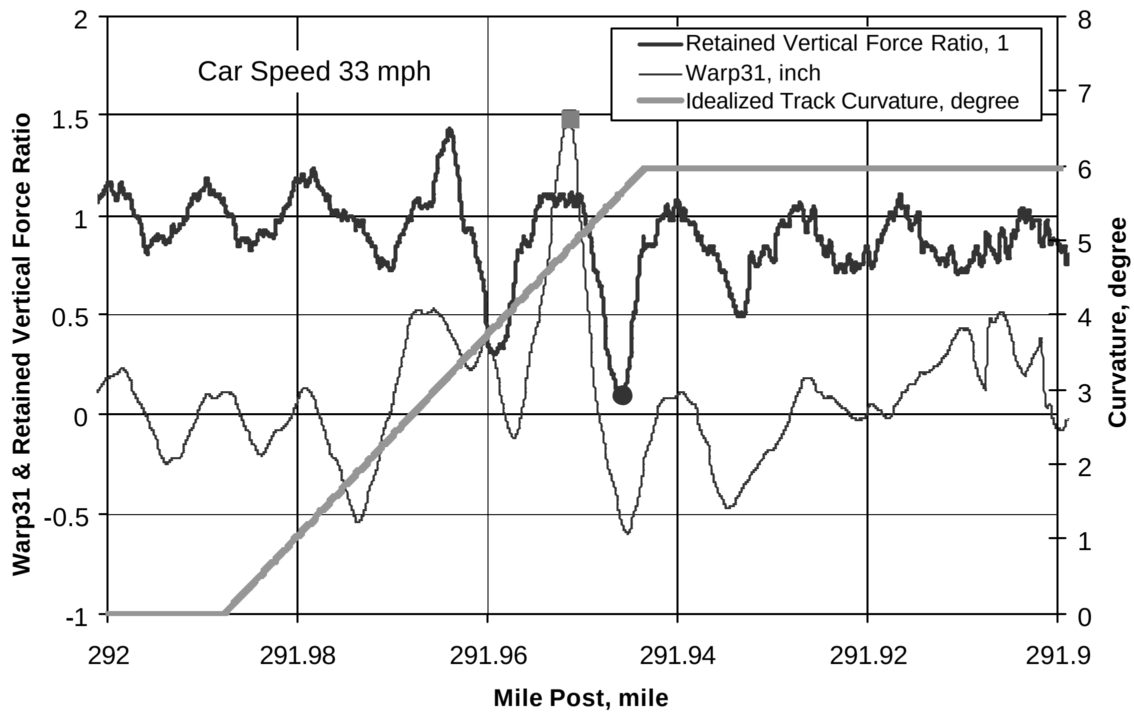

Figure 11 History Plots of "Urgent" Warp31 Defect and Its Corresponding Urgent Force Defect (Retained Vertical Force) around MP291.95

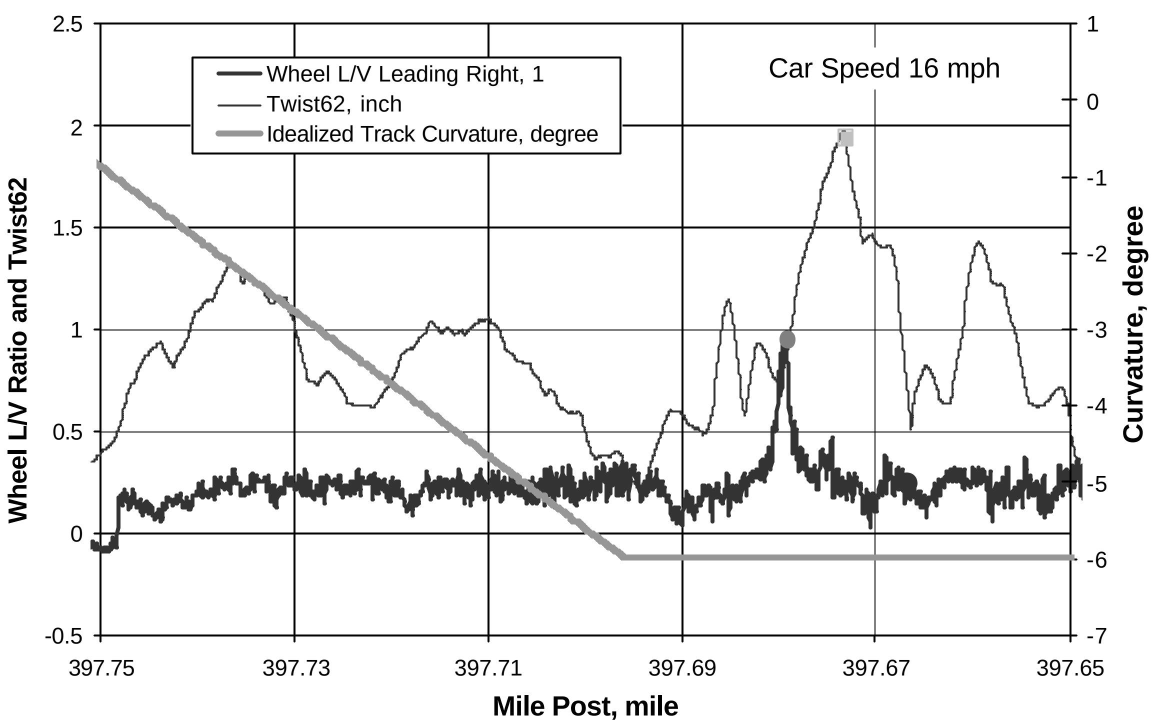

Figure 12 History Plots of "Priority" Twist62 Defect and Its Corresponding "Priority" Force Defect (Wheel L/V Ratio) around MP397.68

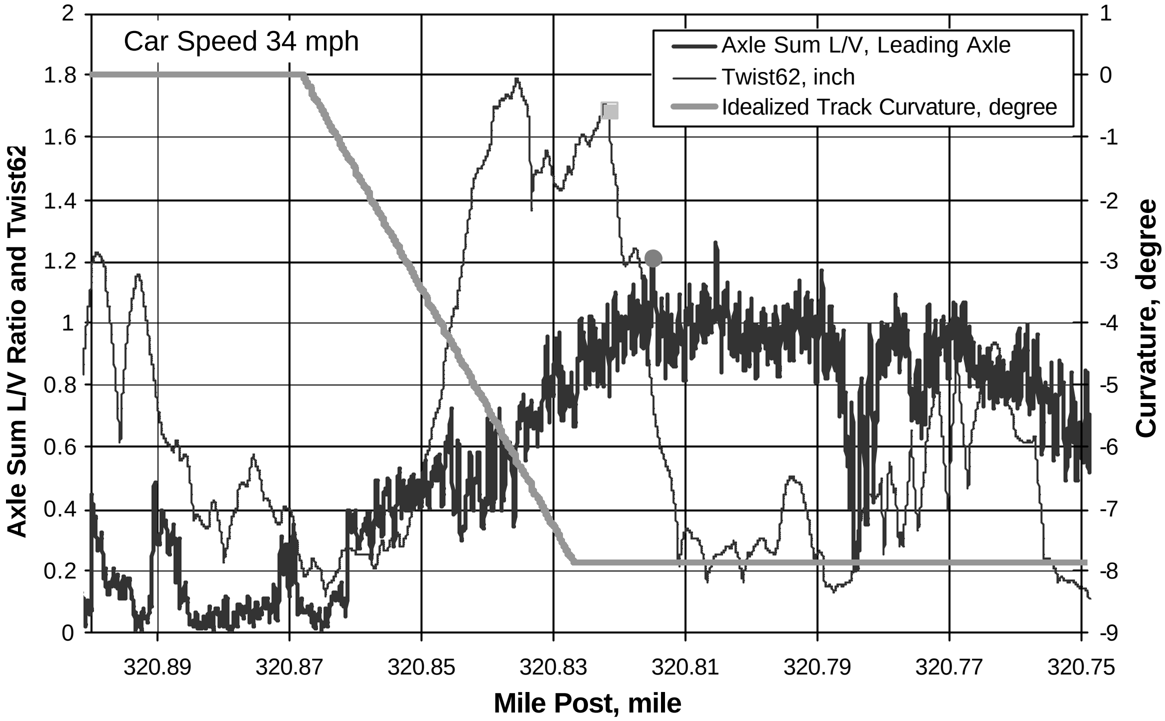

Figure 13 History Plots of "Priority" Twist62 Defect and Its Corresponding "Priority" Force Defect (Axle Sum L/V Ratio) around MP320.82

Table 17 Number of Geometry Defects without Corresponding Force Defect at "Urgent" Levels under Different Speed Rules

Track Type	Geometry Defect **With** Corresponding Force Defect	No Speed Rule		Speed Rule 1: Those Defects with Speed > 90% of Speed Limit		Speed Rule 2: Those Defects with Cant Deficiency > 1.5"	
		All Defects	**Without** Corresponding Force Defect	All Defects	**Without** Corresponding Force Defect	All Defects	**Without** Corresponding Force Defect
Twist62 on Tangents	0	19	19	13	13	5	5
Twist62 on Curves	2	31	29	22	20	13	11
Warp31 on Spirals	9	396	387	285	276	154	145
Defect Violating Speed Rules **but Having** Corresponding Force Defect			0		6		1
Total	11	446	**435**	320	**315**	172	**162**

Table 18 Number of Geometry Defects without Corresponding Force Defect at "Priority" Levels under Different Speed Rules

Track Type	Geometry Defect **With** Corresponding Force Defect	No Speed Rule		Speed Rule 1: Those Defects with Speed > 90% of Speed Limit		Speed Rule 2: Those Defects with Cant Deficiency > 1.5"	
		All Defects	**Without** Corresponding Force Defect	All Defects	**Without** Corresponding Force Defect	All Defects	**Without** Corresponding Force Defect
Twist62 on Tangents	0	8	8	4	4	2	2
Twist62 on Curves	0	10	10	4	4	7	7
Warp31 on Spirals	1	34	33	22	21	18	17
Defect Violating Speed Rules **but Having** Corresponding Force Defect			0		0		0
Total	11	52	**51**	30	**29**	27	**26**

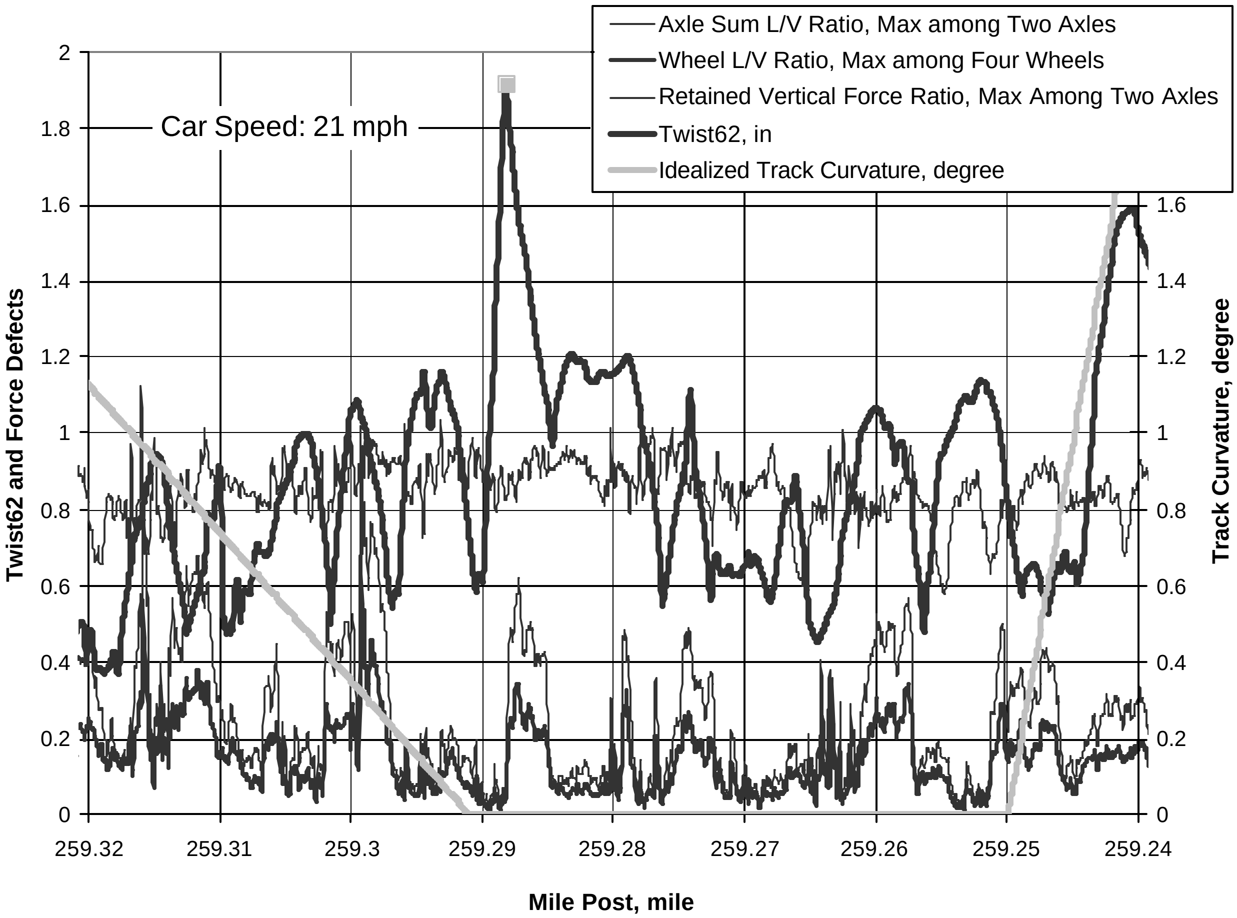

Figure 14 History Plots of an "Urgent" Twist62 Defect and All the Force Defects around It at Mile Post of about 259.29 Mile

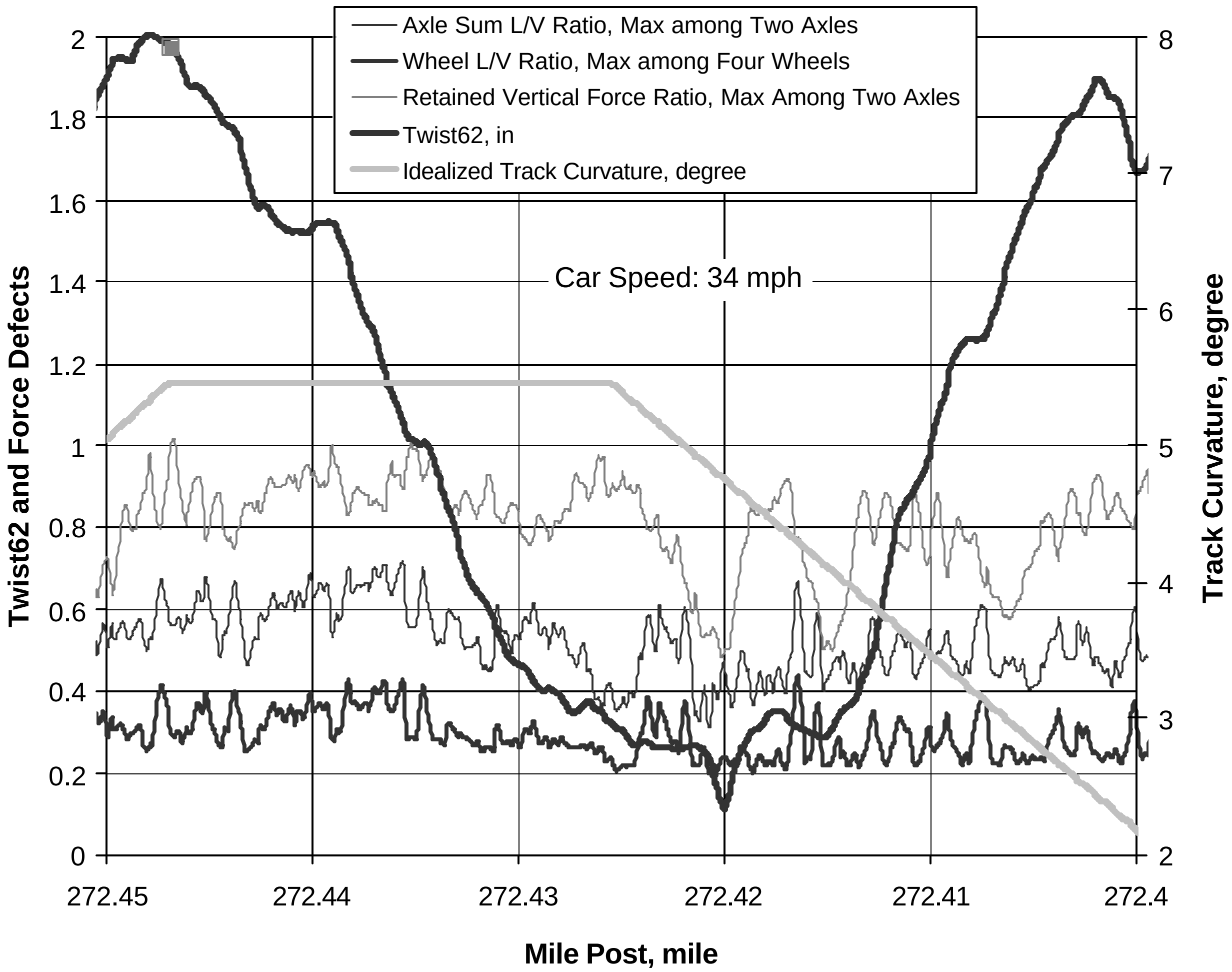

Figure 15 History Plots of an "Urgent" Twist62 Defect and All the Force Defects around It at Mile Post of about 272.45 Mile

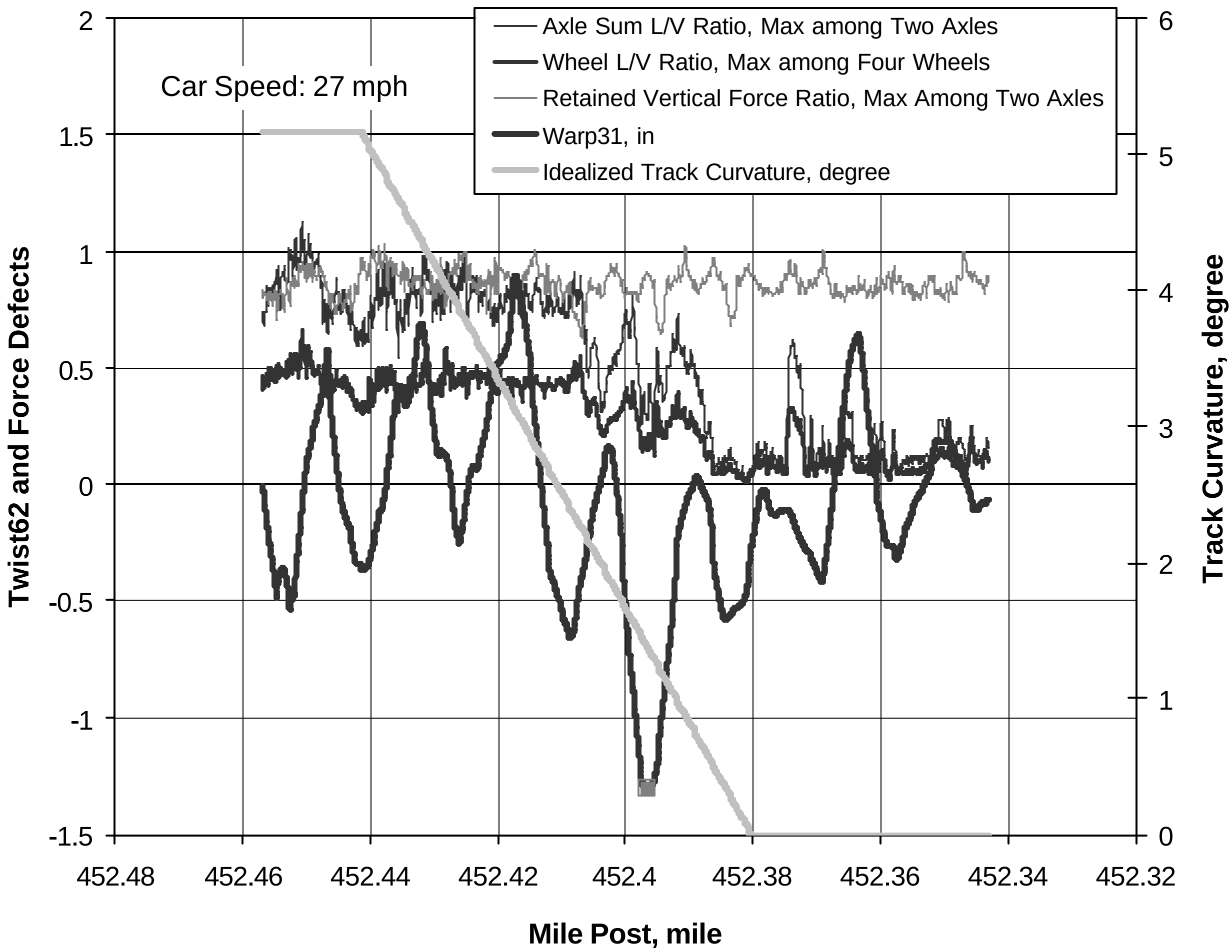

Figure 16 History Plots of an "Urgent" Warp31 Defect and All the Force Defects around It at Mile Post of about 452.4 Mile

Table 19 Number of Force Defects with and without Corresponding Geometry Defect at Both "Urgent" and "Priority" Levels

Track Type	Urgent level			Priority level		
	All Defects	**With** Corresponding Geometry Defect	**Without** Corresponding Geometry Defect	All Defects	**With** Corresponding Geometry Defect	**Without** Corresponding Geometry Defect
Tangents	1	0	1	8	0	8
Curves	6	0	6	39	2	37
Spirals	1	1	0	23	11	12
Total	8	1	**7**	70	13	**57**

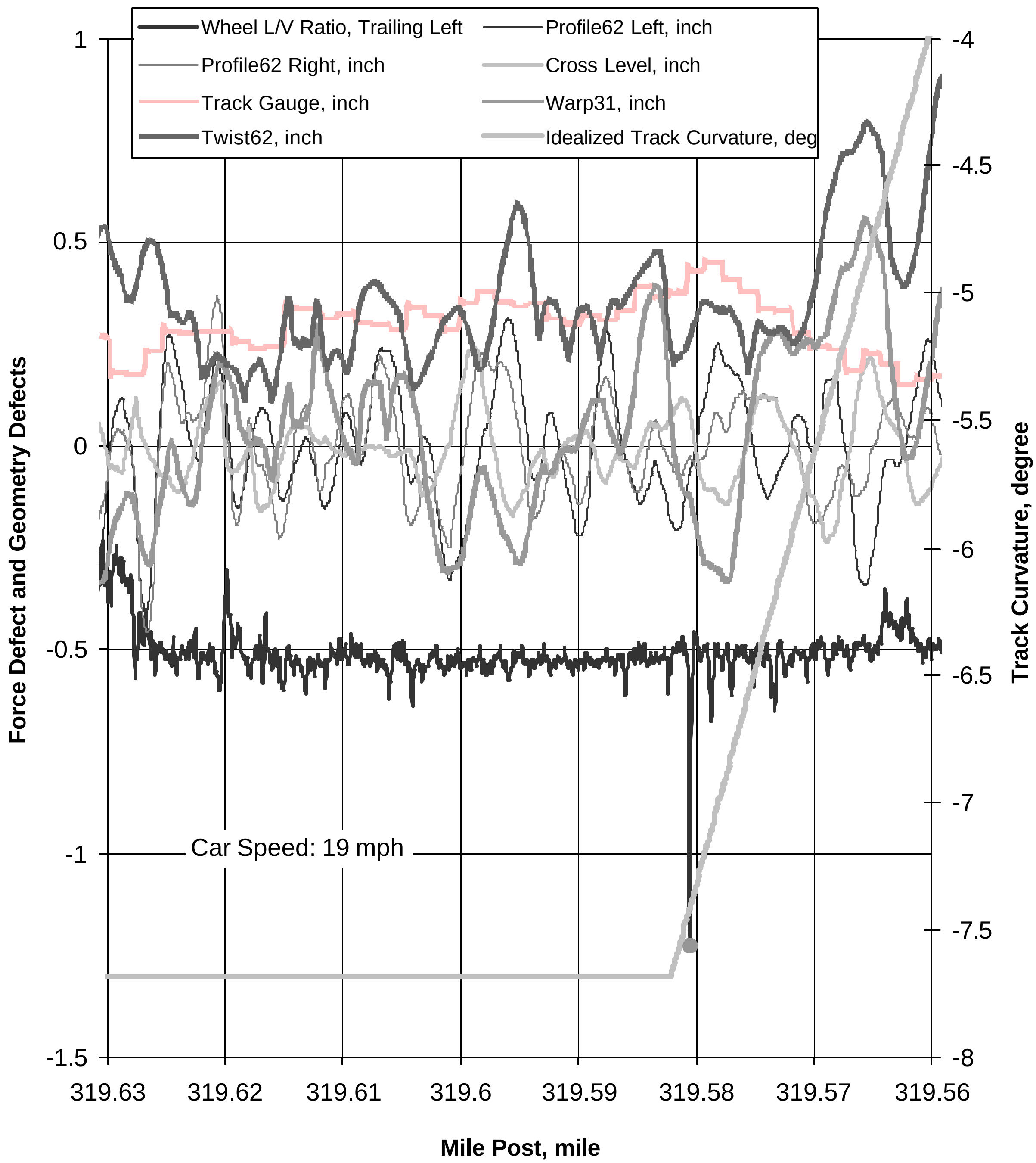

Figure 17 History Plots of Unmatched Force Defect and All the Geometry Variations around It, Case 1

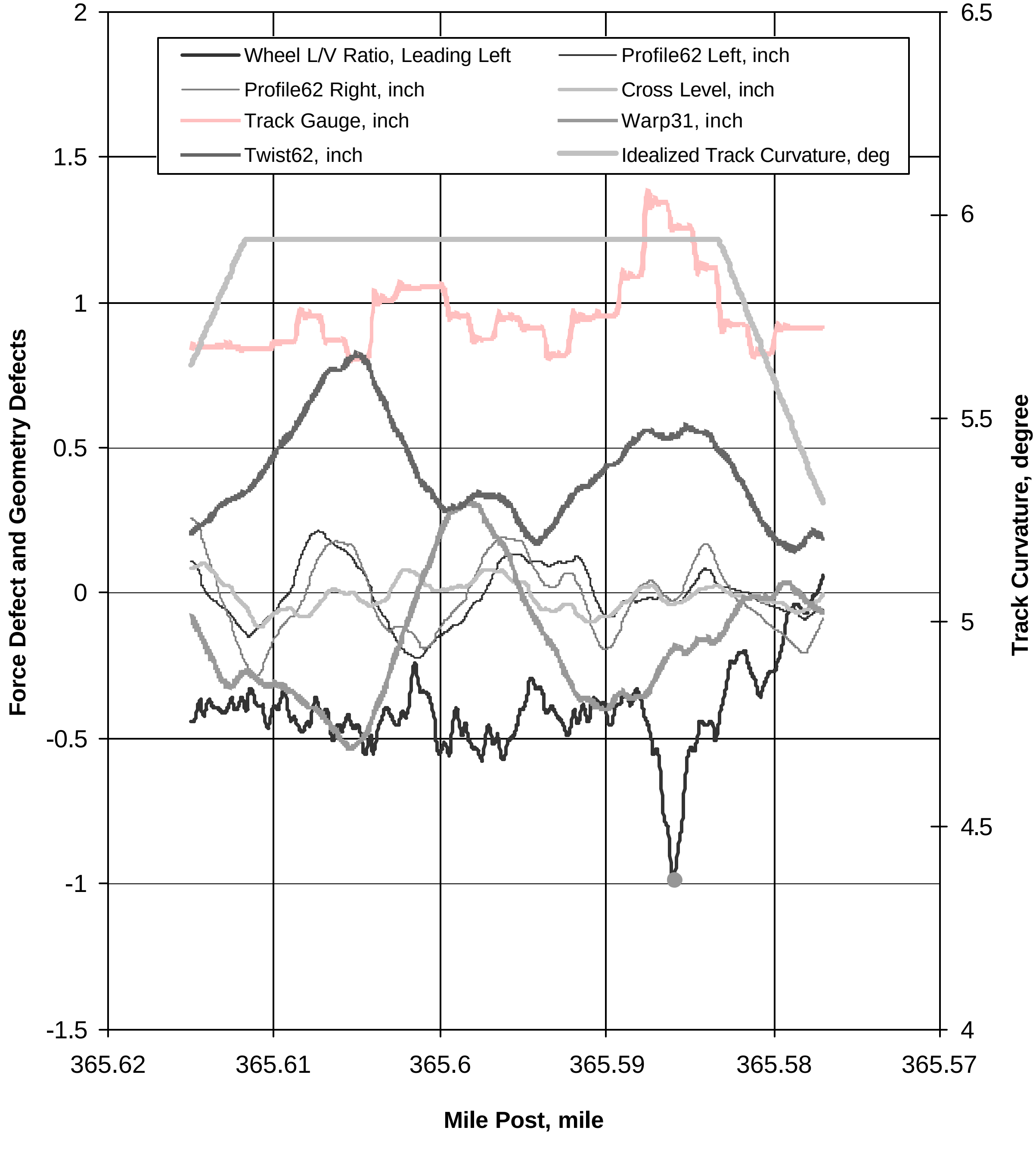

Figure 18 History Plots of Unmatched Force Defect and All the Geometry Variations around It, Case 2

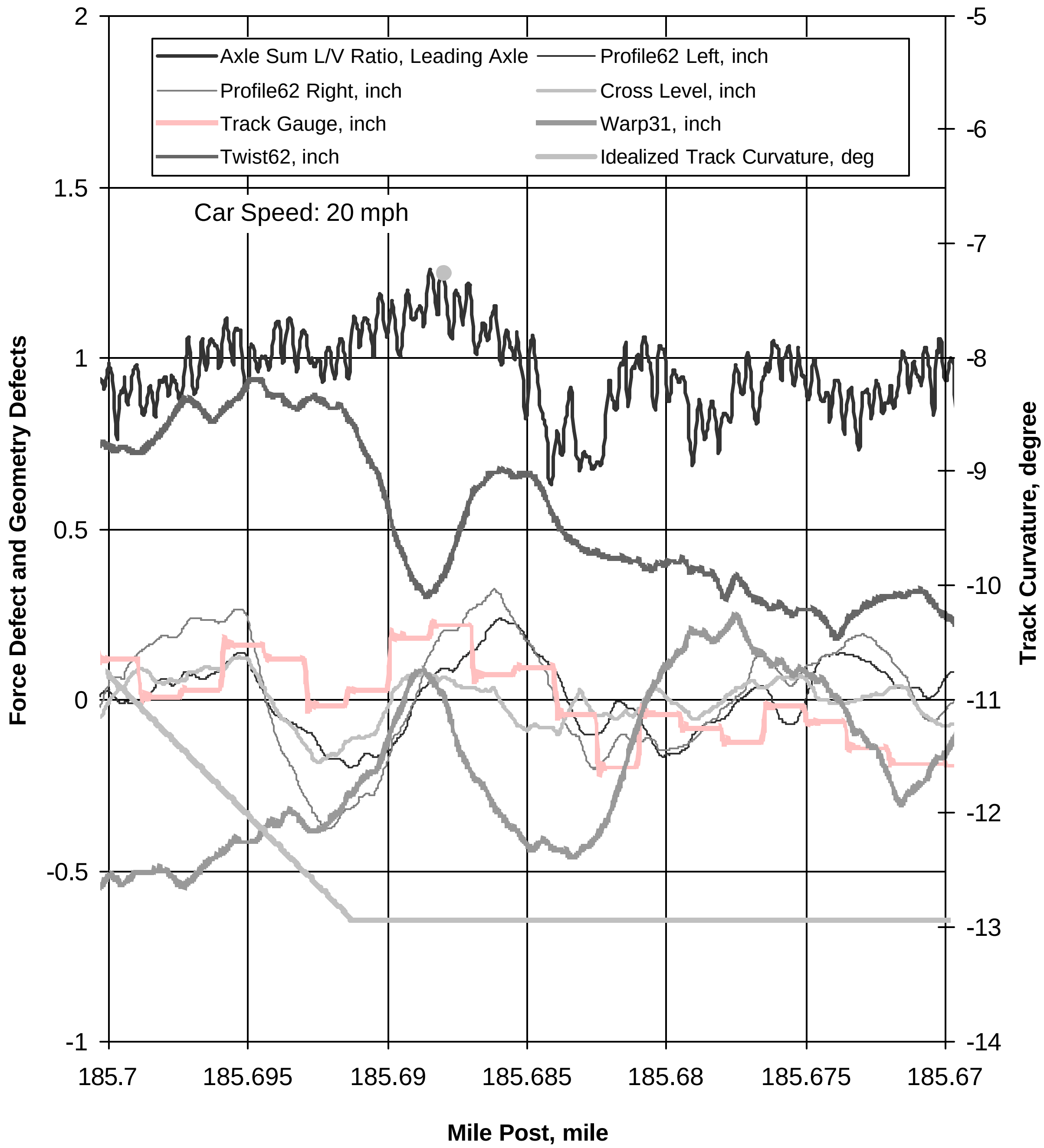

Figure 19 History Plots of Unmatched Force Defect and All the Geometry Variations around It, Case 3a

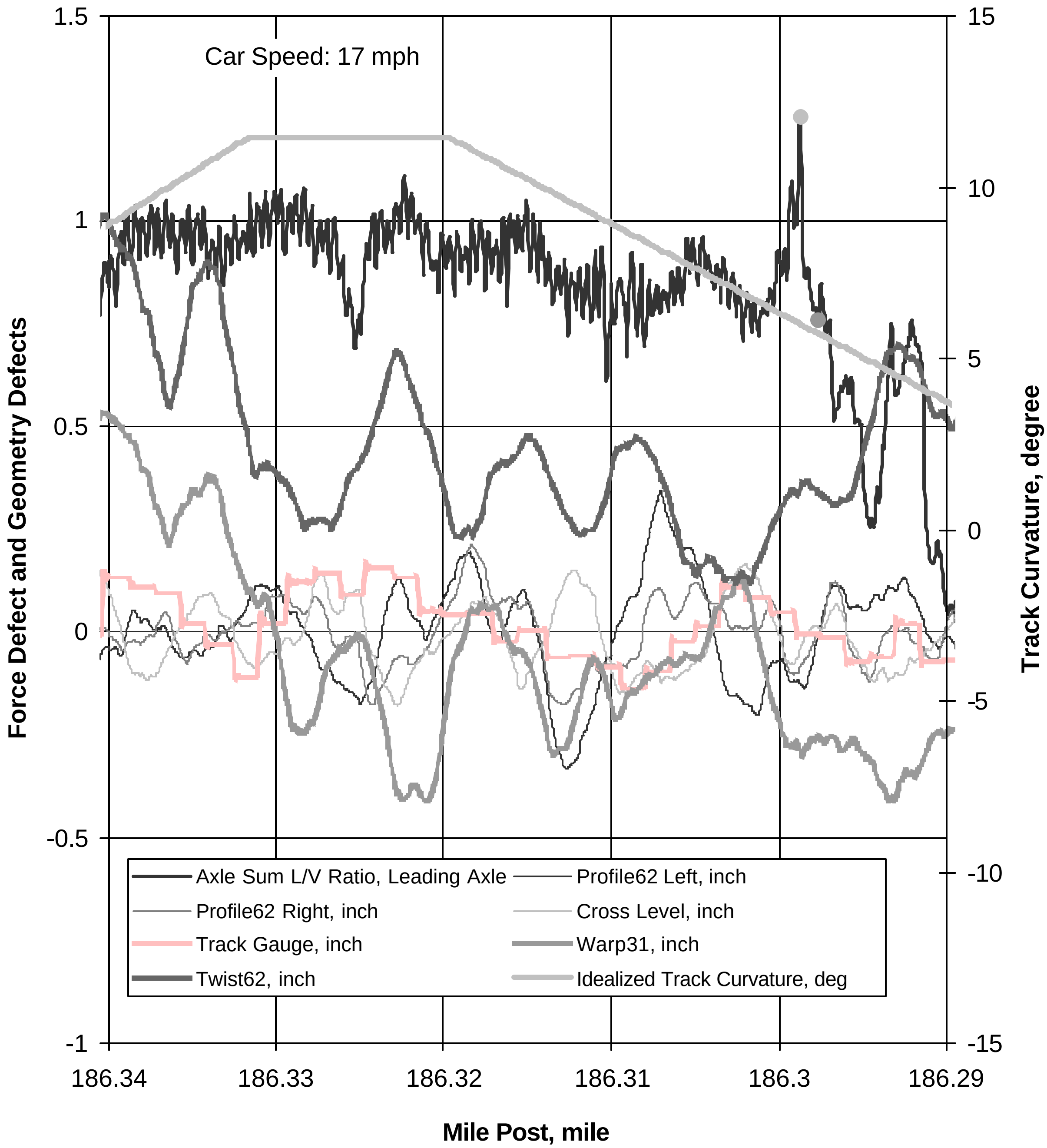

Figure 20 History Plots of Unmatched Force Defect and All the Geometry Variations around It, Case 3b

Table 20 Correlation Coefficients for Relations between Track Geometry Parameters and Wheel Force Ratios

Track Geometry Type	Track Type	Track Parameter	**Retained Vertical Force Ratio**	**Wheel L/V Ratio**	**Axle L/V Ratio**
Track Surface Variations	Spirals	**Warp31**	0.542	0.063	0.051
	Tangents	**Twist62**	0.332	0.010	0.001
	Curves	**Twis62**	0.485	0.068	0.086
	All	**Profile**	0.248	0.017	0.054
	All	**Cross Level**	0.386	0.151	0.071
Track Gauge	All	**Wide Gauge**	0.233	0.243	0.188
Track Alignment	All	**Alignment**	No Test Data		

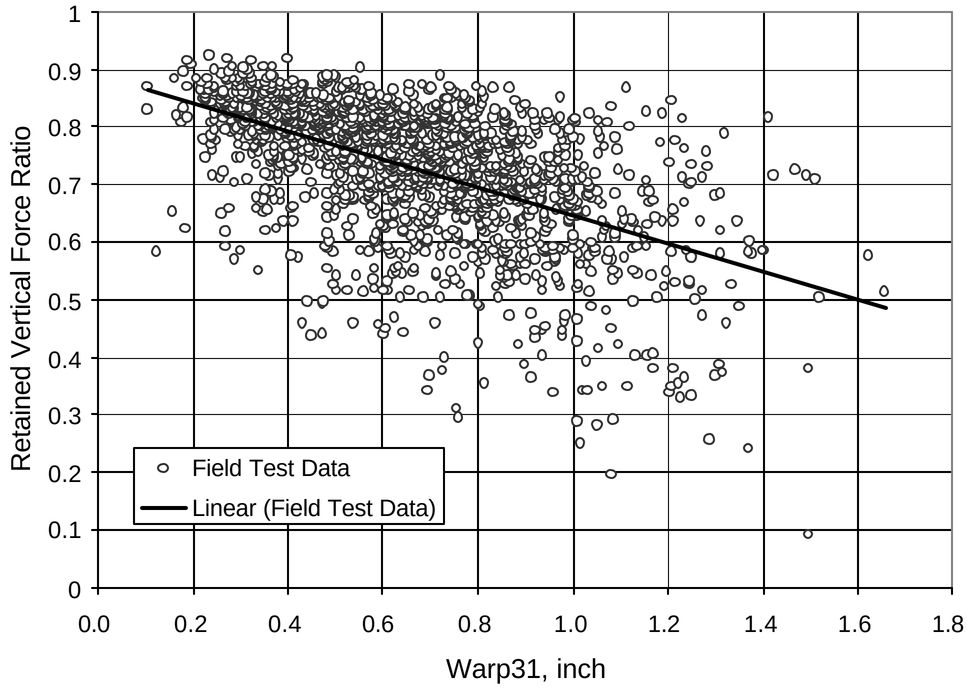

Figure 21 Relation between Retained Wheel Vertical Force Ratio and Warp31 on All Spiral Track Sections of Field Test

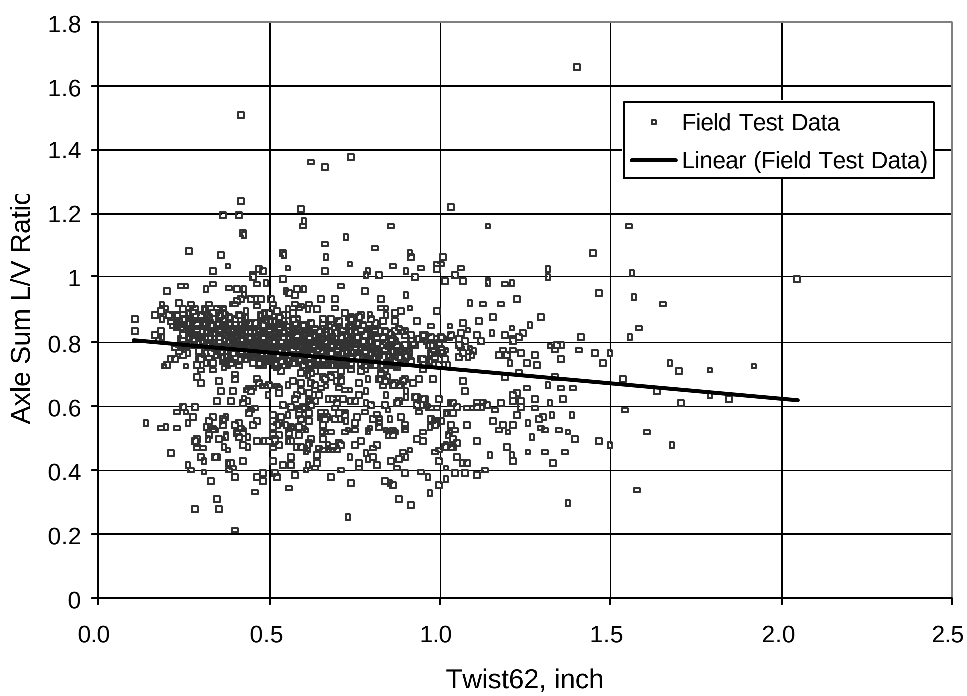

Figure 22 Relation between Axle Sum L/V Ratio and Twist62 on All Tangent and Curve Body Sections of Field Test

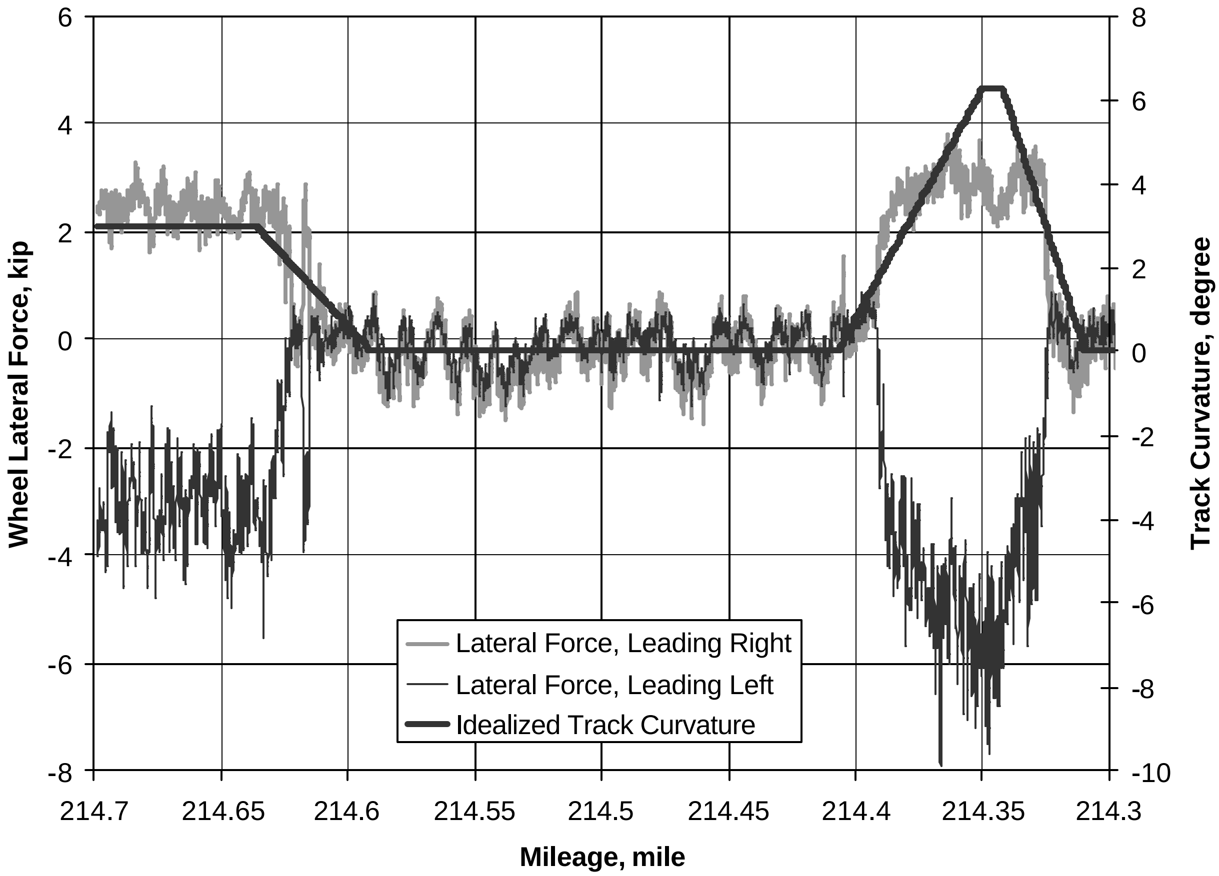

Figure 23 Typical History Plot of Wheel Lateral Forces and Track Curvature

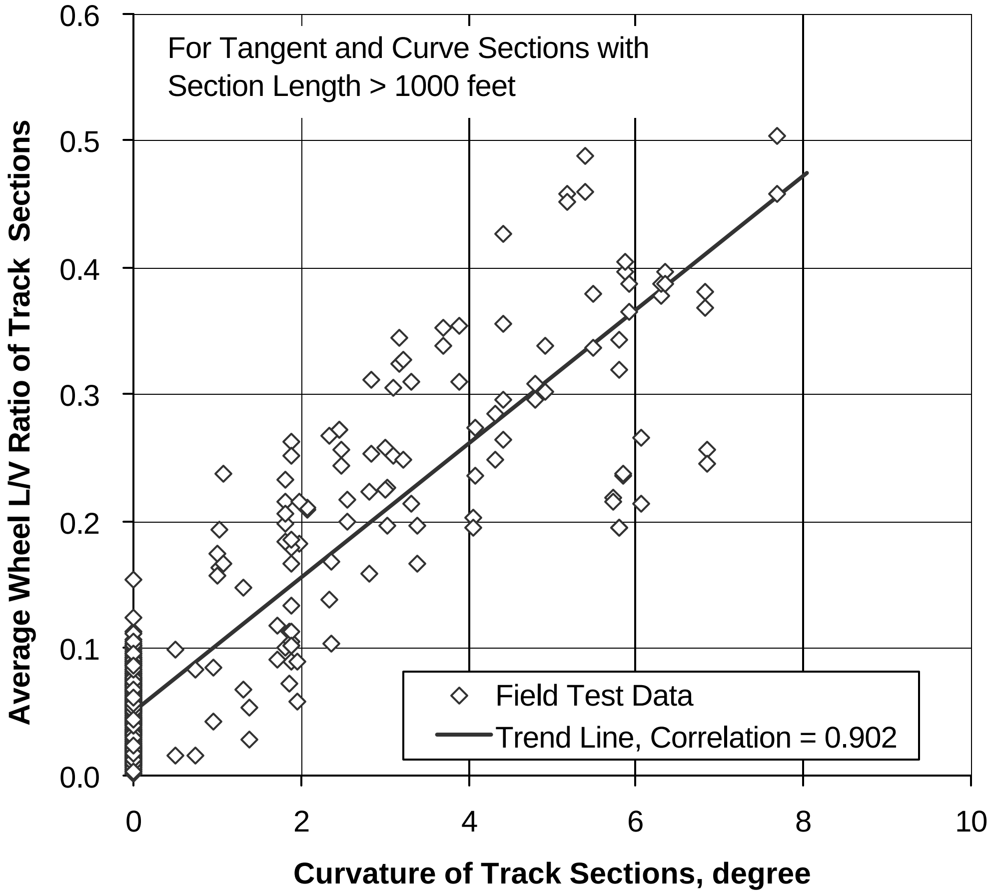

Figure 24 Average Wheel L/V Ratio as Function of Degree of Curve for Tangent and Curve Sections of Tested Track

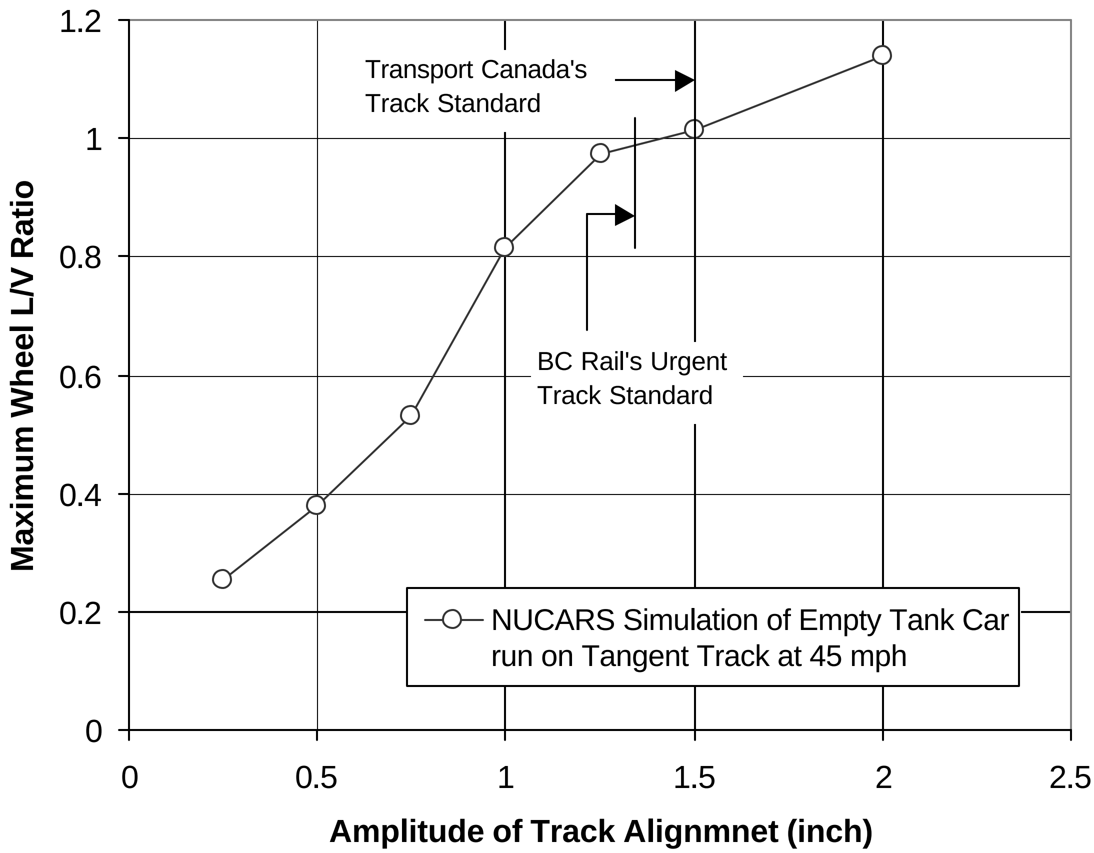

Figure 25 Relation between Wheel L/V Ratio and Track Alignment from NUCARS Simulation

APPENDIX A HISTORIES OF ALL EIGHT "URGENT" FORCE DEFECTS AND THE RELEVANT GEOMETRY DEFECTS

The present analysis results show **only one of eight urgent force defects had the matched geometry defect**. It therefore becomes very important to clarify **what the causes are for the other seven force defects**, even though this is a task that is beyond the scope of this project.

For this aspect, the history plots for all eight force defects as listed in Table A1 were built. The histories of the force defect and the relevant geometry defects around the force defect are included in Figures A1 to A8 (for force defect numbers 1 to 8). From these plots, one can see that:

(1) Except for force defect no.2, all the other force defects are preceded by obvious increases of one or more geometry parameters. The observation results for the force-geometry relationships are summarized in Table A1.

(2) In most cases, there exist two or more geometry variations around a force defect. Although each geometry variation has an individual error value smaller than the track standards, a combination of these geometry errors can produce a force defect.

(3) Track alignment is an important link for the force-geometry relationship being investigated. Track alignment data were not available for the present project. The importance of track alignment is indicated by the fact there are four force defects out of eight that have some connection with the track gauge.

Therefore, much better correlation between wheel force defects and track geometry defects can be expected if the combination of track geometry errors and the track alignment defect are included in the investigation. This will depend on future research.

Table A1 Summary of the Causes for All Eight "Urgent" Force Defects

Force Defect				Geometry Defect									Cause of the Force Defect
				Warp31			Twist62			Gauge			
No.	Name	Value	Location (Mile)	Value	Location	Level*	Value	Location	Level*	Value	Location	Level*	
1	**Retained Vertical Force (%)**	**8.66%**	**291.943**	**1.495**	**291.952**	**3**							**Warp31**
2	Wheel L/V Ratio	1.230	319.578				0.591	319.595	0	0.40	319.593	0	Unknown
3	Wheel L/V Ratio	1.085	390.671				1.364	390.671	1	1.22	390.670	1	Twist62 and Gauge (Alignment)
4	Axle Sum L/V Ratio	1.510	428.556	0.655	428.561	0	0.956	428.555	0	0.29	428.550	0	Twist62 and Warp31
5	Axle Sum L/V Ratio	1.503	205.633	0.772	205.640	2	1.471	205.640	1				Twist62 and Warp31
6	Wheel L/V Ratio	0.999	365.585							1.38	365.596	3	Gauge (Alignment) and Twist62
7	Wheel L/V Ratio	0.995	311.351							0.80	311.361	0	Gauge (Alignment) and Twist62
8	Wheel L/V Ratio	0.991	259.340				1.405	259.34	0	0.91	259.346	1	Twist62 and Gauge (Alignment)

* Level is defined as:
  - Level 0 - below BC Rail's priority limit, but is the maximum value in the track section
  - Level 1 - between BC Rail's priority and BC Rail's urgent limits
  - Level 2 - between BC Rail's urgent limit and Transport Canada's limit
  - Level 3 - above Transport Canada's limit

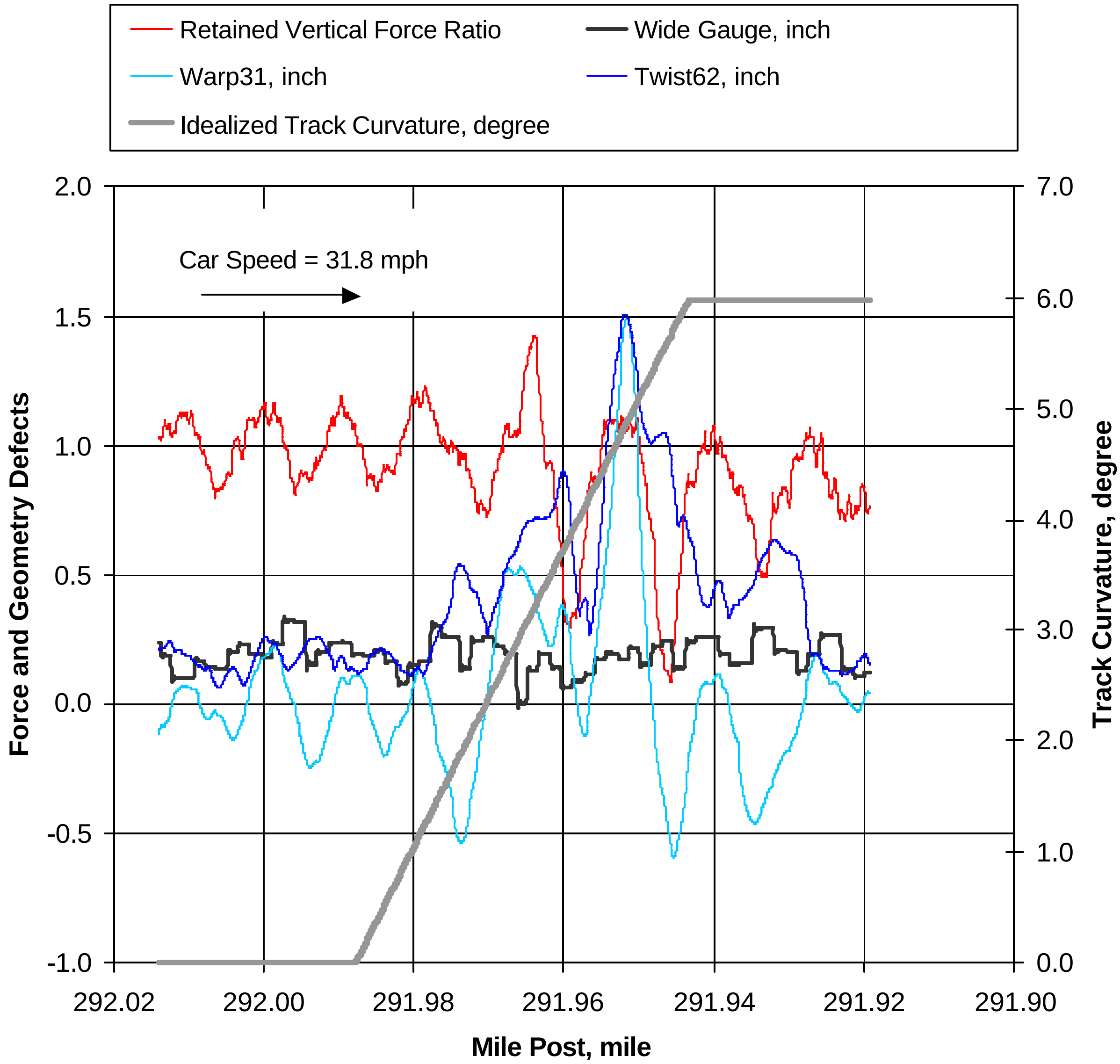

Figure A1 Force Defect No. 1

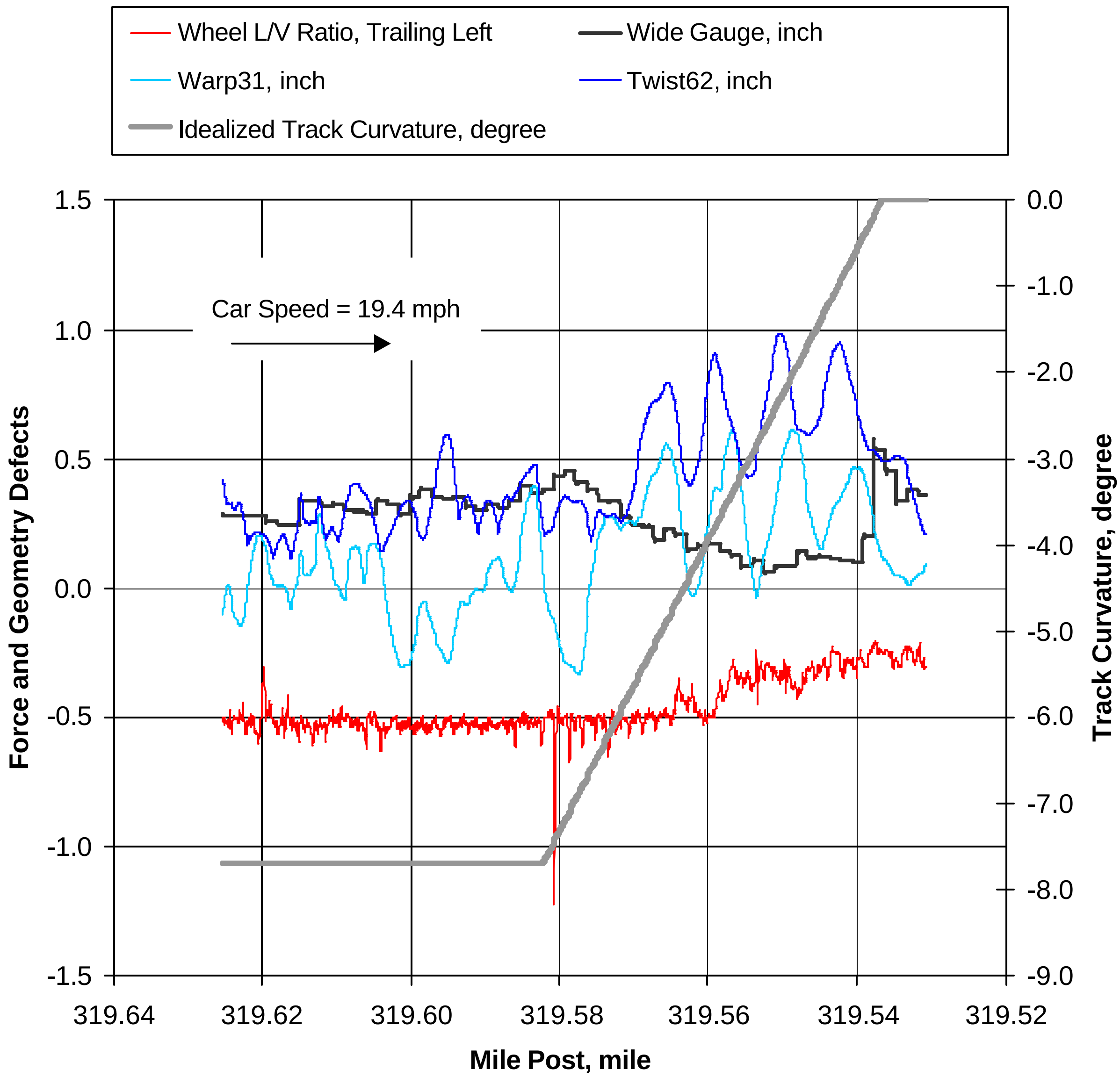

Figure A2 Force Defect No. 2

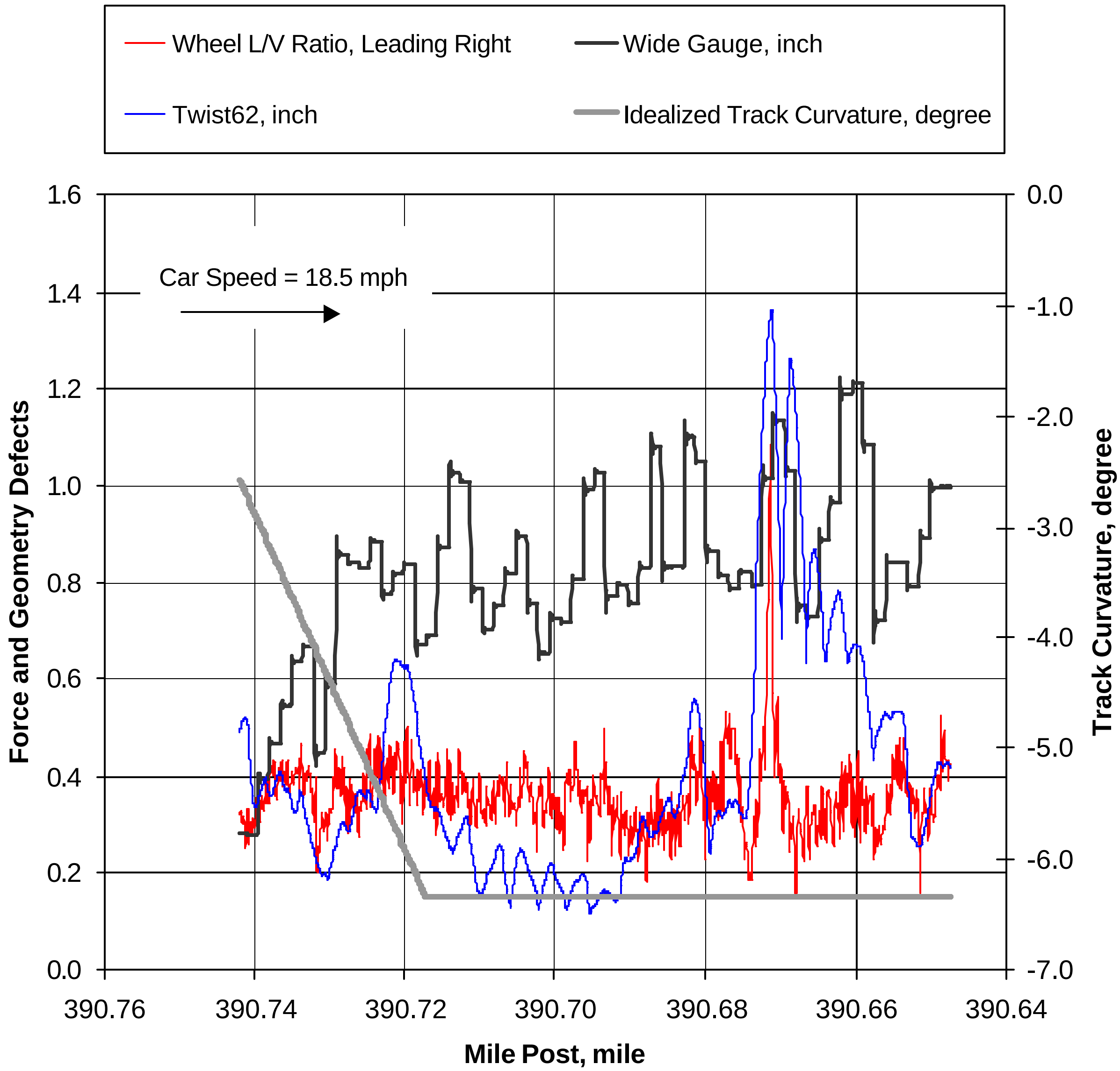

Figure A3 Force Defect No. 3

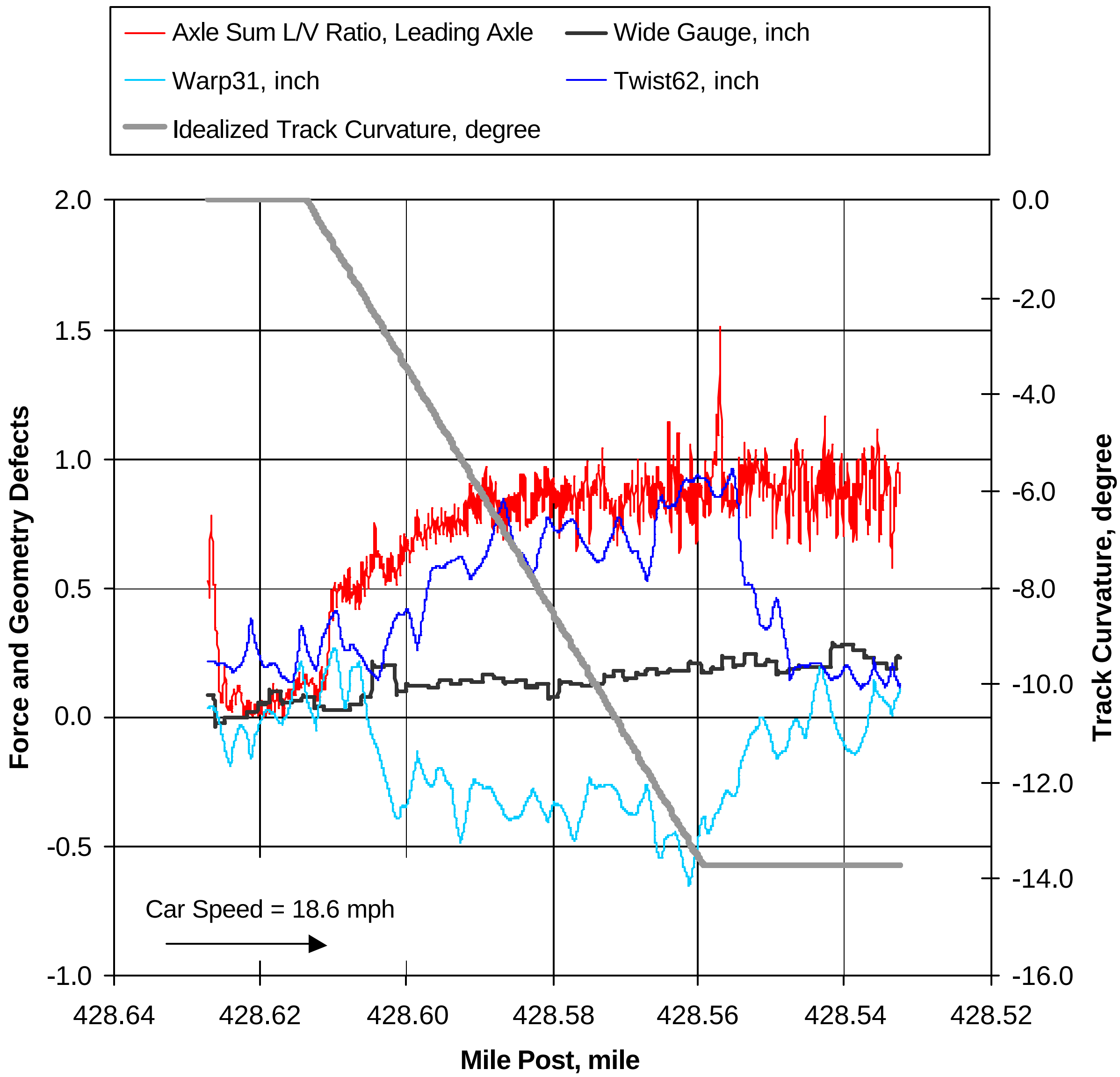

Figure A4 Force Defect No. 4

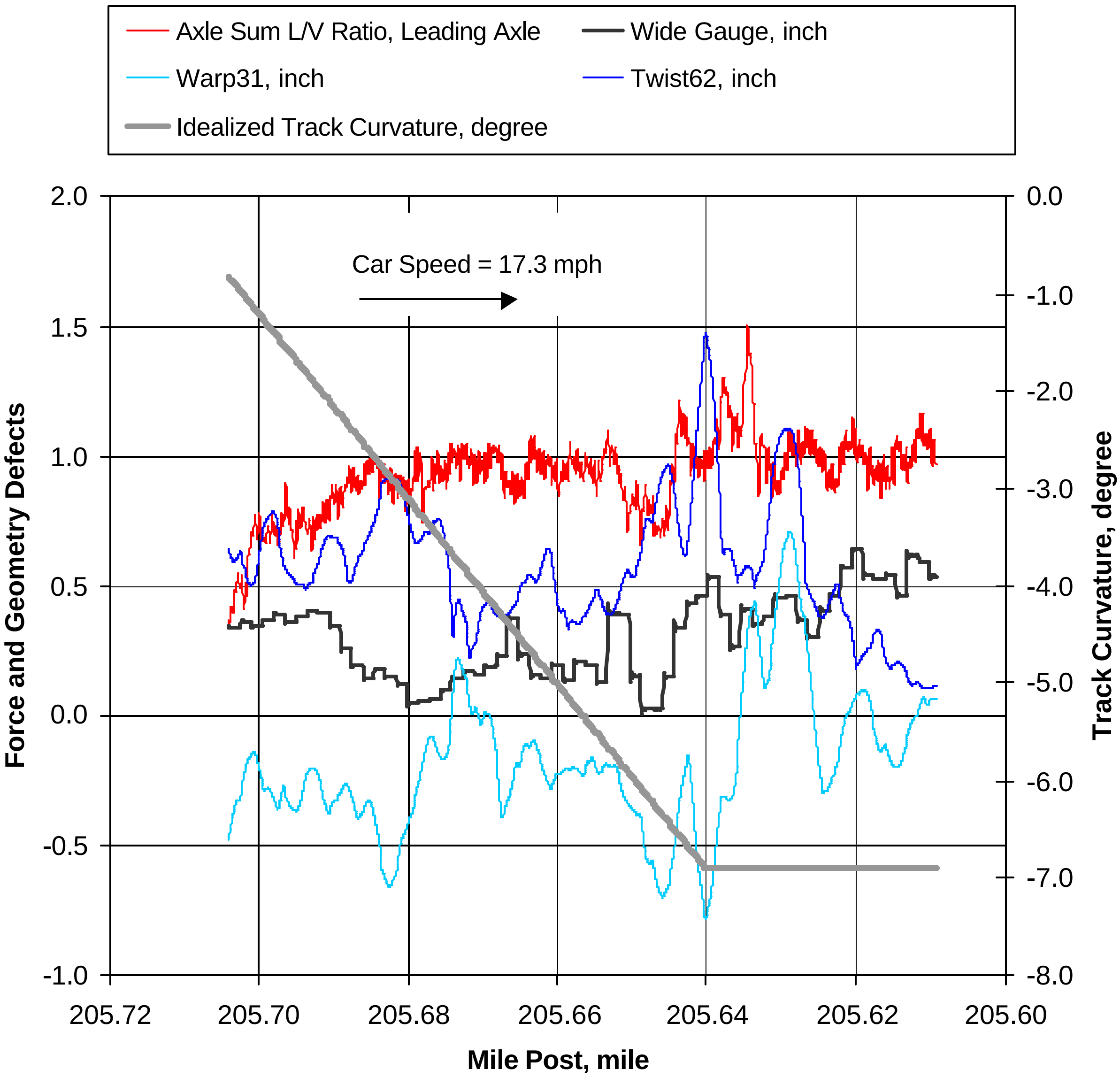

Figure A5 Force Defect No. 5

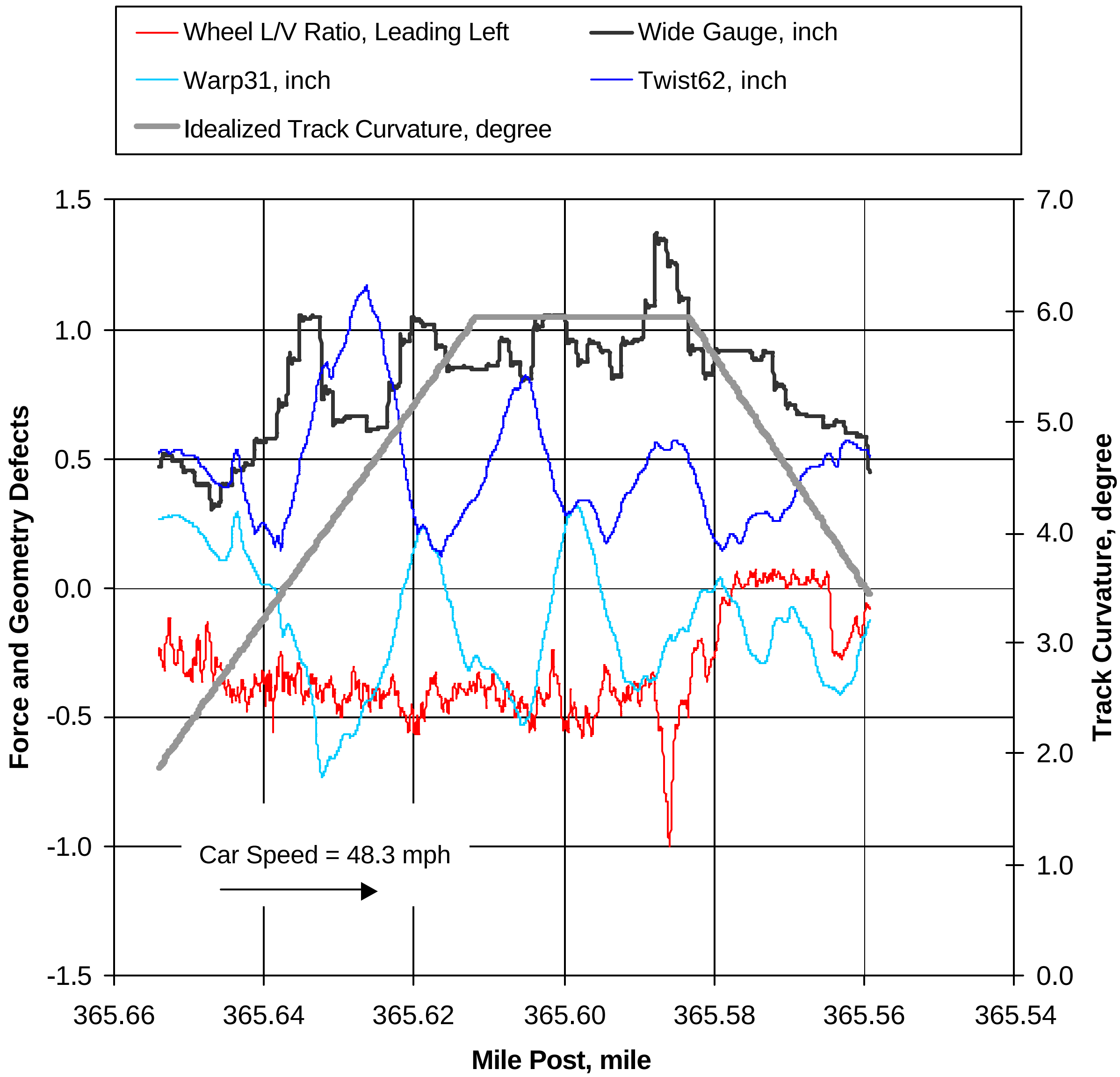

Figure A6 Force Defect No. 6

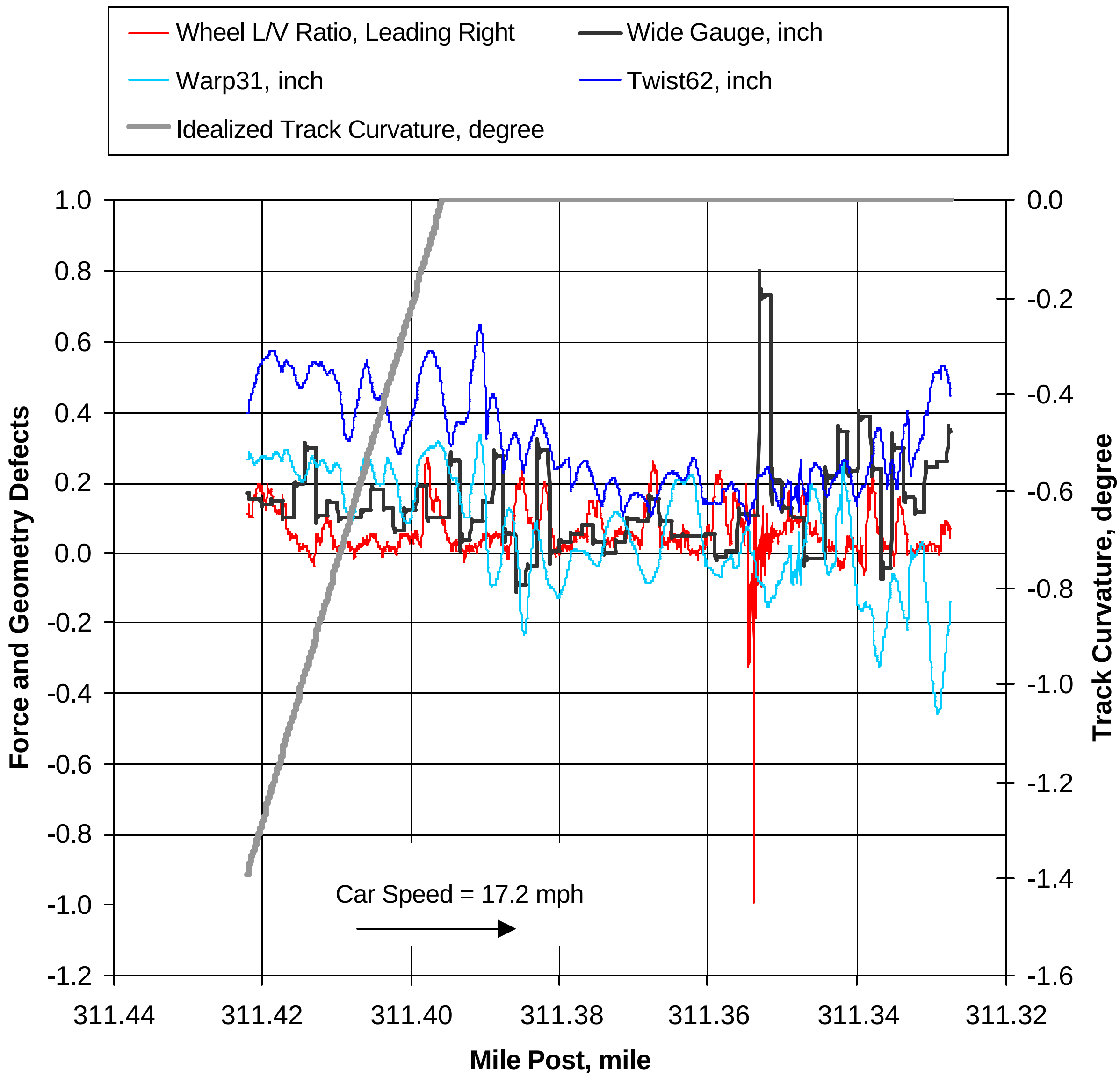

Figure A7 Force Defect No. 7

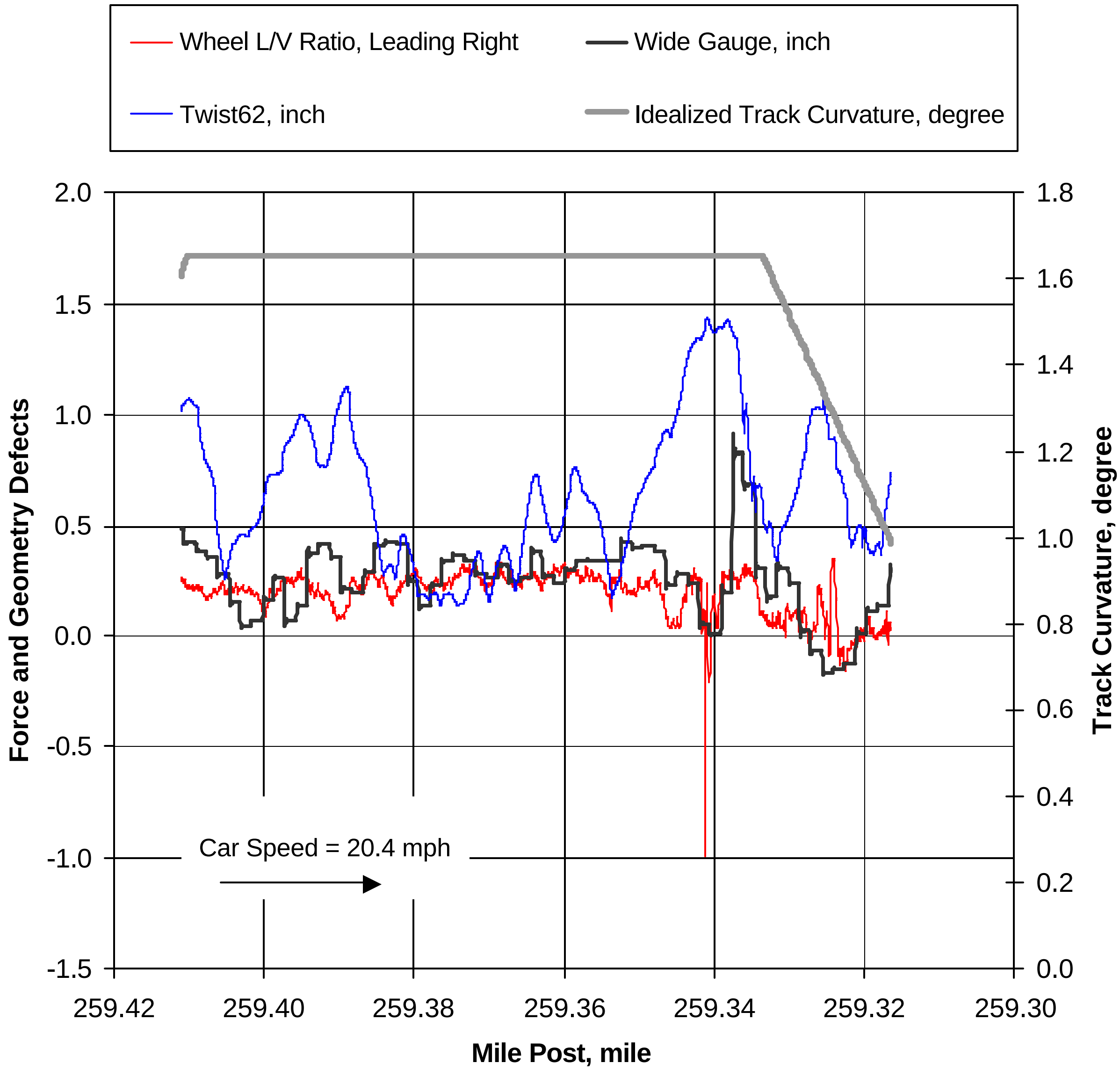

Figure A8 Force Defect No. 8