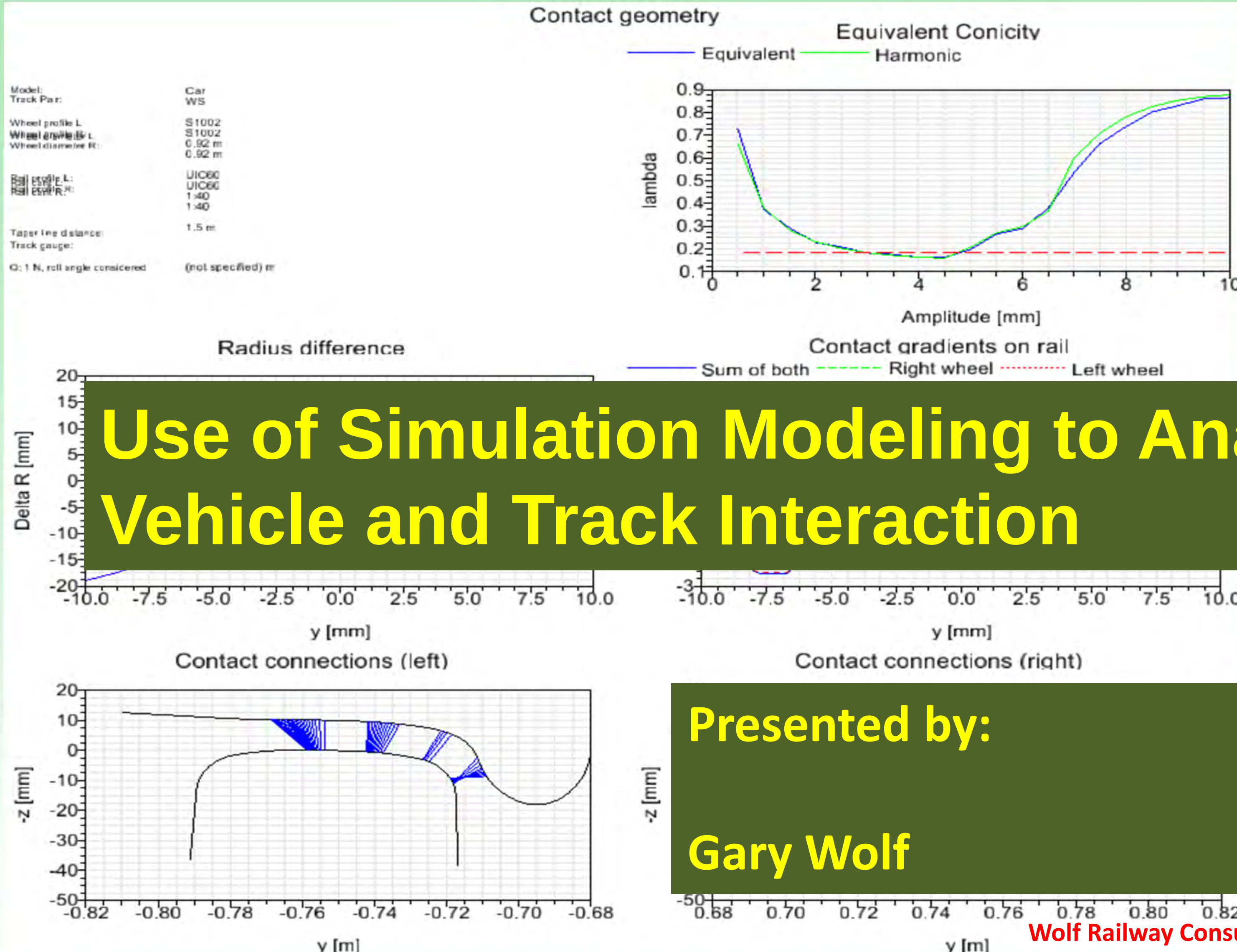

Use of Simulation Modeling to Analyze Vehicle and Track Interaction

Presented by:

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Computer Simulation Models used in Train and Vehicle Dynamics

- Train Operations Simulator (TOS)
- Train Operations and Energy Simulator (TOES™)
- NUCARS™, VAMPIRE, SIMPACK, GENSYS, ADAMS RAIL, Universal Mechanism (UM)

Simulation – the imitation of the operation of a real-world process or system over time Wikipedia

Simulation - the representation of the behavior or characteristics of one system through the use of another system, especially a computer program designed for the purpose. Dictionary.com

Simulation - the imitative representation of the functioning of one system or process by means of the functioning of another <a computer *simulation* of an industrial process> Webster

2 Kinds of Simulation

- Deterministic
  - Based on laws of physics and uses real world inputs
    - ✓Excellent when there is certainty about inputs
- Probabilistic or Stochastic
  - Based on probabilities of something happening, often using random or defined probability distribution of various inputs
    - ✓Excellent when there is uncertainty about inputs

Advantages of Simulation

- Re-create the impossible
- More cost effective than testing
- Can perform many “what if’s”
- Removes Opinions and Biases
- Consistent Methodology
- Proven results; all models validated

Two Types of Simulation Models in Railway Dynamics

- Simulation of longitudinal train dynamics; coupler to coupler forces in a moving train

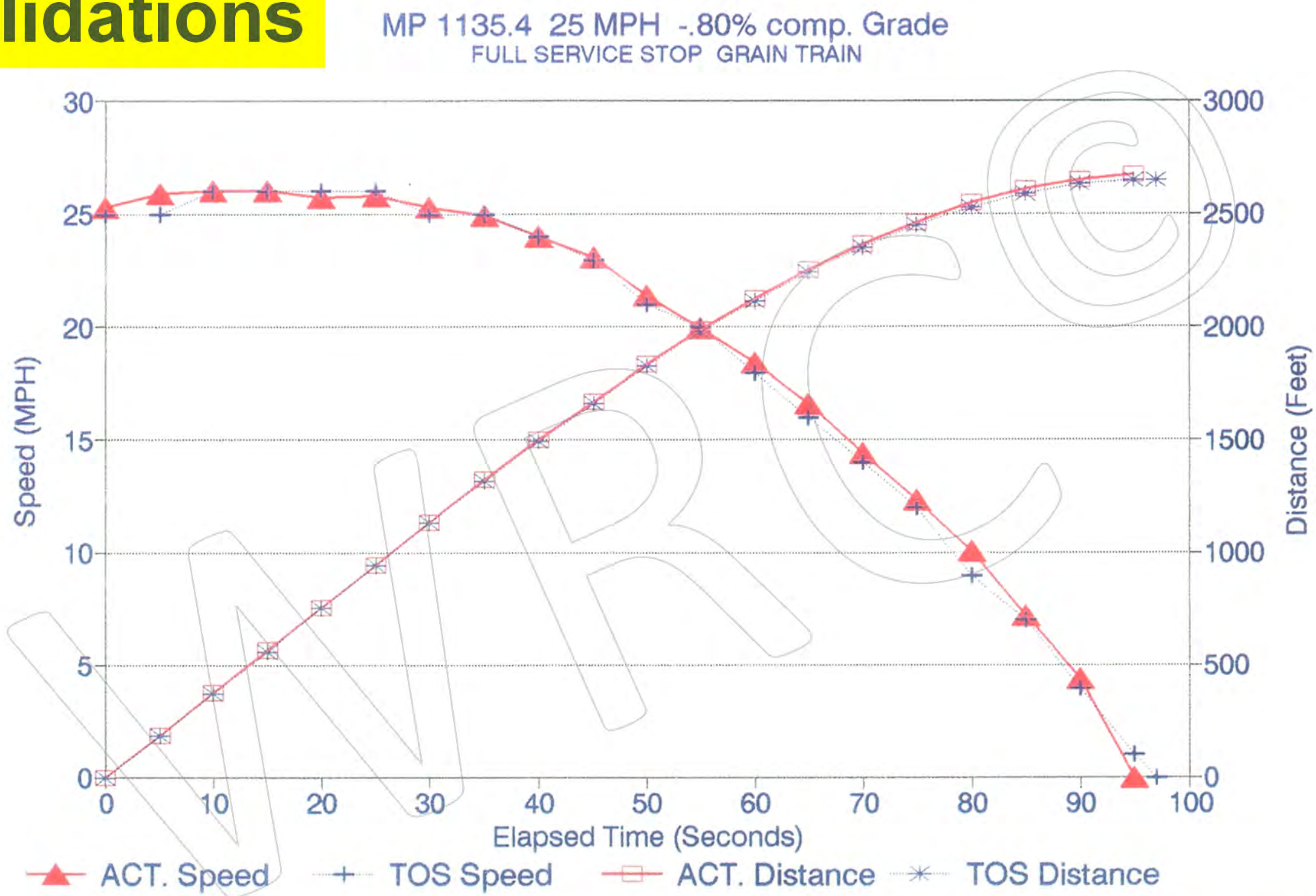
- Simulation of individual vehicle dynamics

TOS Model

- Developed in early 70's by AAR and industry group of TTD Officers
- Developed in FORTRAN for DEC Mainframe Computer
- Well Validated by rail industry
- Primarily Longitudinal Dynamics
- Predict Speeds and Coupler Forces
- Slack Action
- Useful for Train Stopping distances
- Limited to 2 Locomotive Positions in train
- Downside
  - Cannot adequately model EOC devices
  - Cannot adequately model articulated connectors

Examples of Validations of TOS braking performance calculations

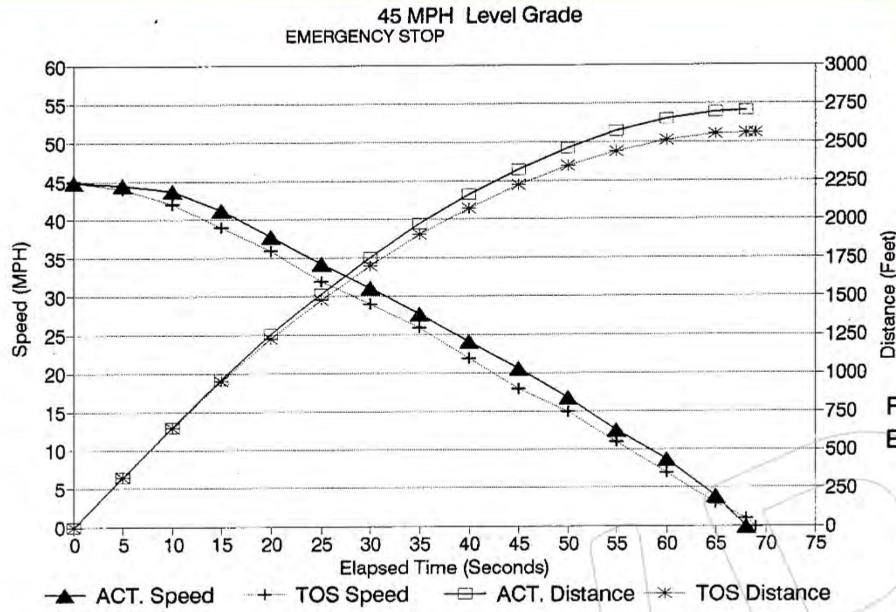
Validations



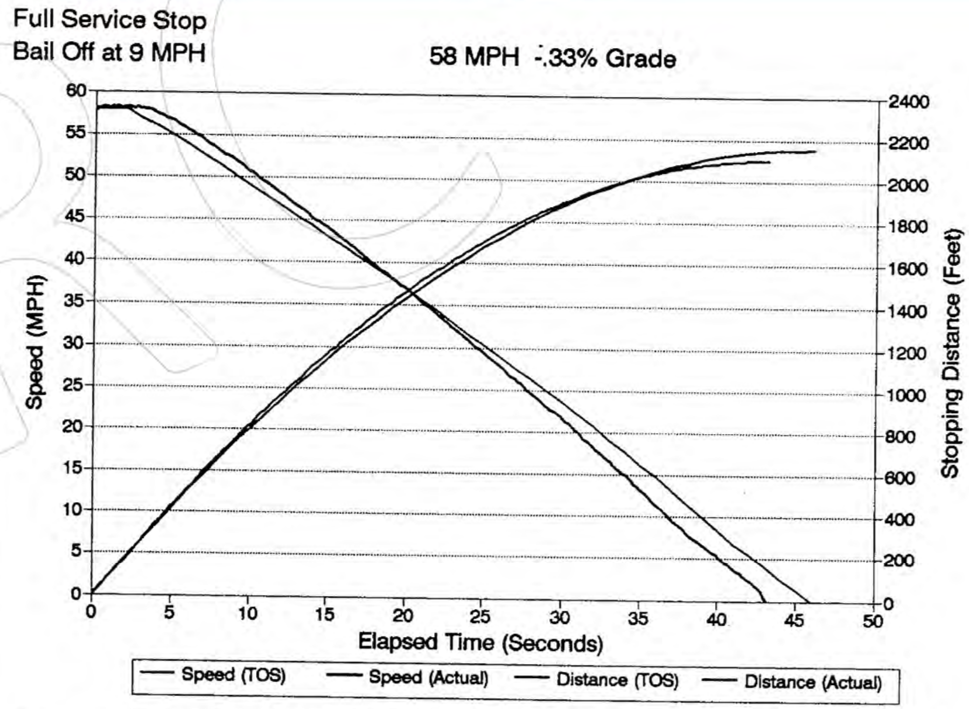
5 Locos, 108 Grain 15,390 Tons (143 T./Car), 2 Helpers 100 PSI TL
Actual Distance = 2674' TOS Distance = 2651' Error = -.86%

Exhibit 6A

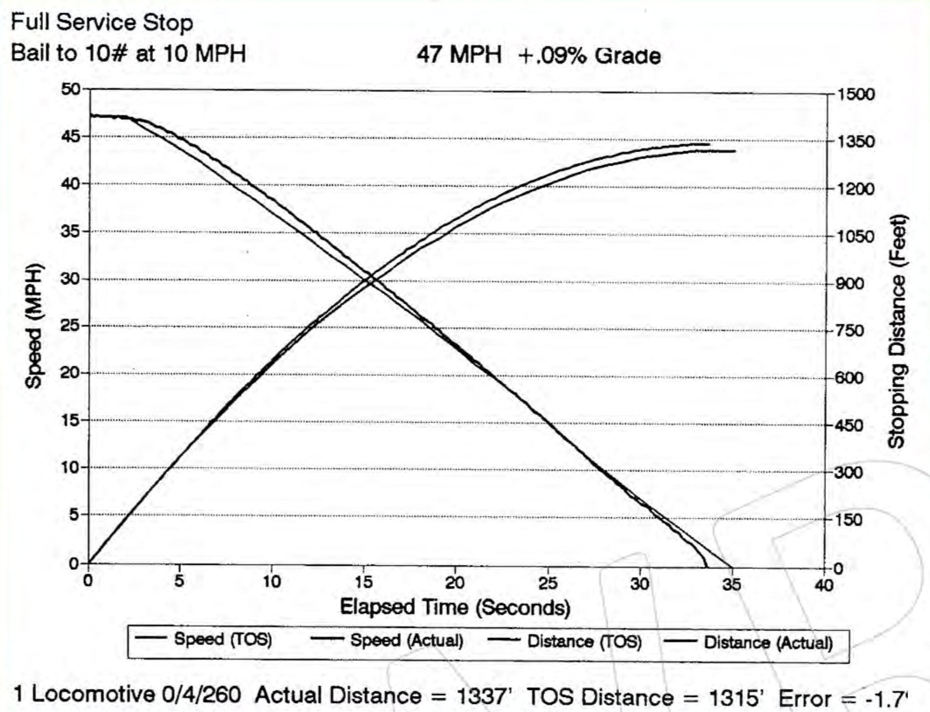
Validations



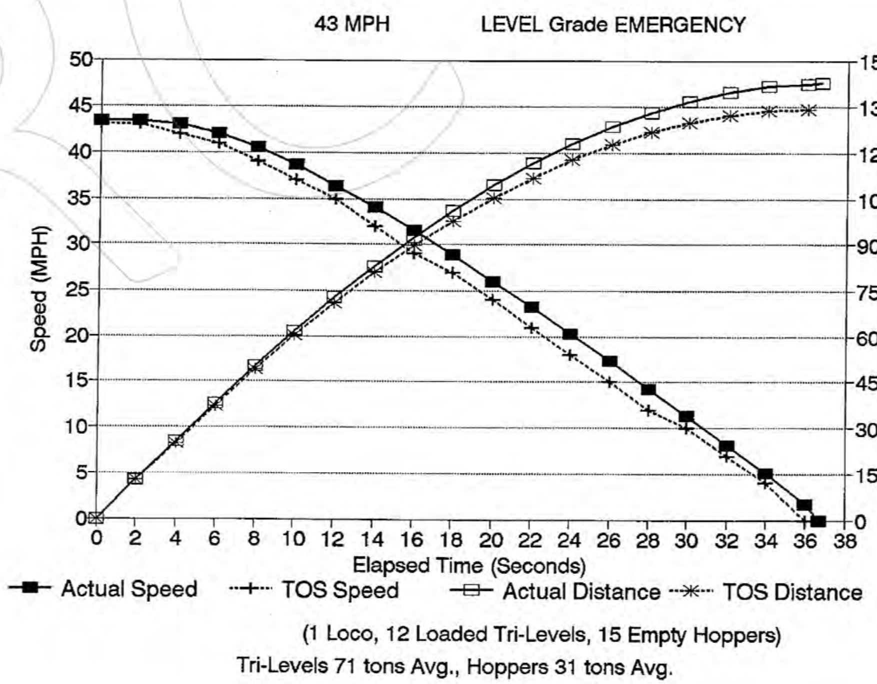
5 Locos, 54 Grain
Actual Distance = 2704' TOS Distance = 2561' Error = -5.29%



1 Locomotive 0/4/260 Actual Distance = 2099' TOS Distance = 2154' Error = +2.6%



Validations



Conclusions TOS Validation

- Over 200 instrumented and measured stop test validations have been performed
  - Typical accuracy +/- 3%
- Numerous instrumented drawbar tests on loaded coal and grain trains
  - Typical accuracy +/- 5% accuracy in steady state pulling or buff
  - +/- 15% accuracy in predicting the magnitude of slack events
  - Very accurate on predicting location and timing of slack
- Nearly every Class 1 railroad in North America has successfully used the TOS Model

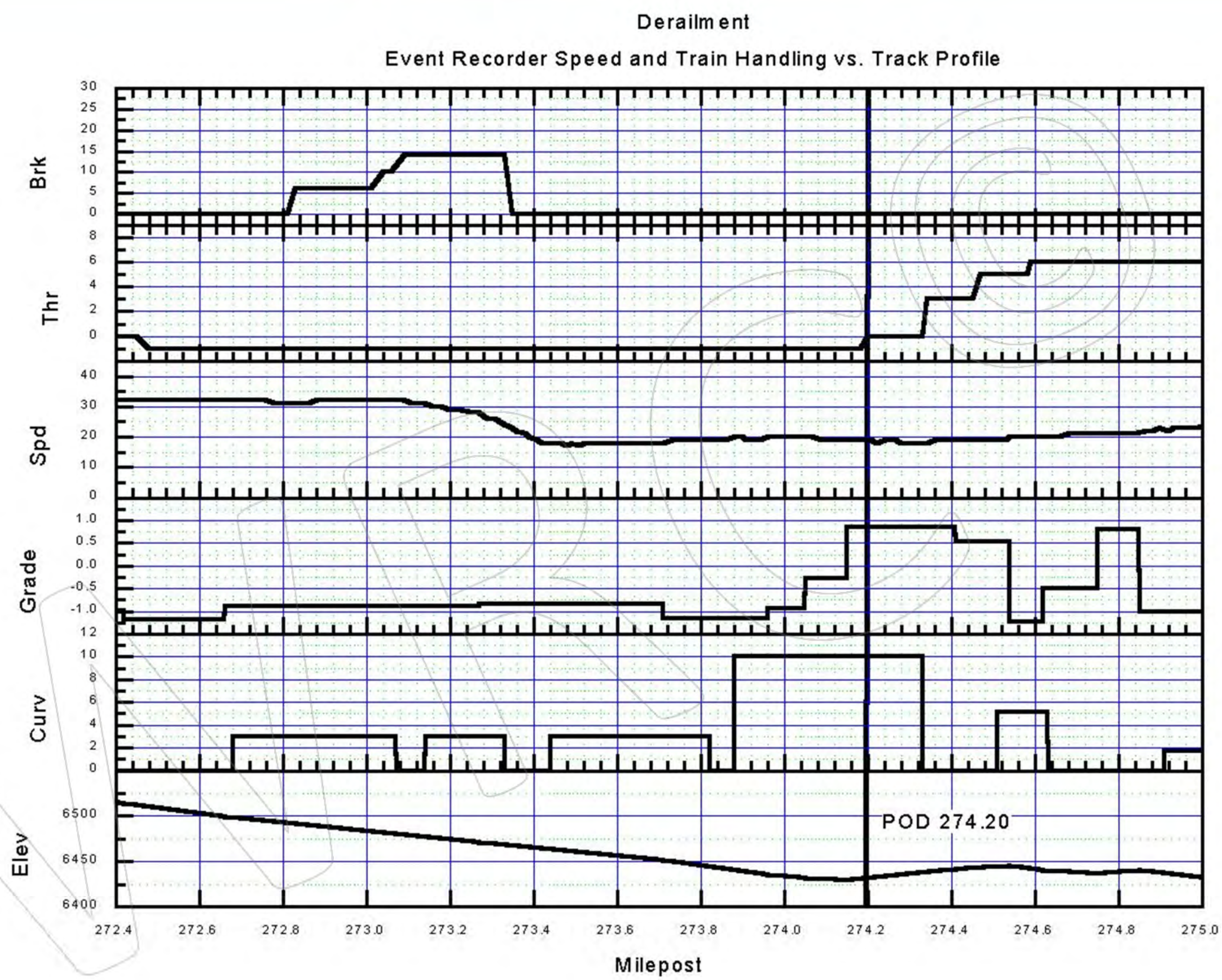
Simple TOS FORTRAN Input File

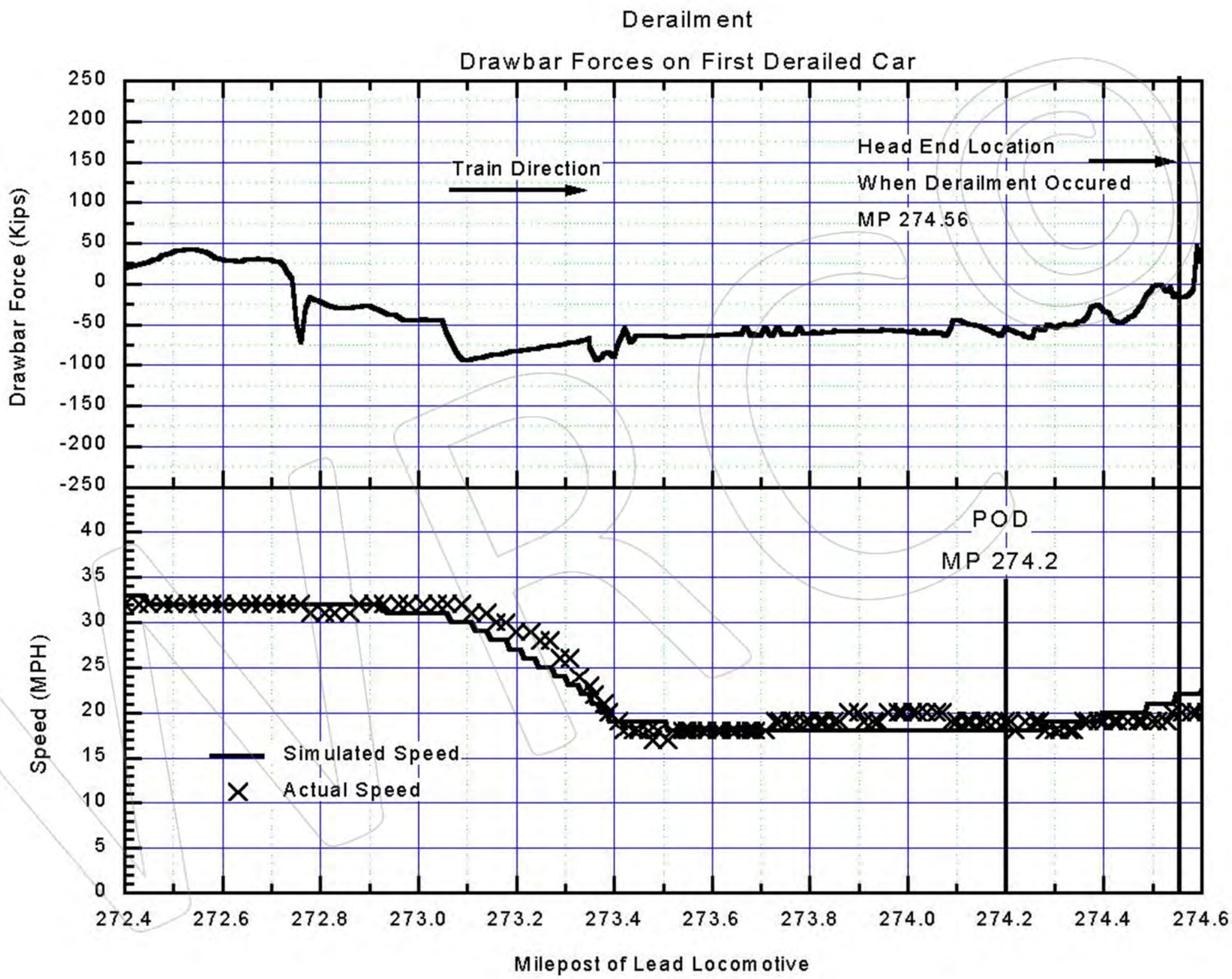
```
REVERSE
 37.0080.  80.  42.00
 42.00     666
  9.  42.      0.00          38.70     38.80
  4.  41.      0.00          38.9      39.10
  3.  31.      0.00          39.1      39.20
  3.  21.      0.00          39.3      39.50
  3.  20.      0.00          39.6      39.80
                                                   LAST
0370006568     0420010000                                    LAST
LAST
O2            SD6072. 199                       CF CP     90
O72           LB5 56.  83                       CF CP     23
             LAST
WI
FORCES 1 2 74
B P 80
L 3
P   1
IDLE
START 38.8 20 MPH
B E
BAIL
C 0 MPH
STOP
```

TOS Output File

```
                                BRAKES      MAXIMUMS    ACCEL          FOR SPECIFIED VEHICLES
   STATION      SPEED  THTLE AMPS SETTING PRESSURE  (AND LOCATION)  MPH PER   POSI  IDENTIFIER      DRAWBAR FORCES      L/V
 TIME      MP   LMT RUN          TRN IND PIPE CYL KIPS:CAR L/V:CAR SEC MIN   TION               FORE       AFT    RATIO

-----> USE WIDE CARRIAGE FORMAT FOR OUTPUT DATA
-----> PRINT OUT FORCES ON VEHICLE   1
-----> PRINT OUT FORCES ON VEHICLE   2
-----> PRINT OUT FORCES ON VEHICLE  74
-----> USE  80 P.S.I. BRAKE PIPE PRESSURE
-----> LEAKAGE = 3 P.S.I. PER MINUTE
-----> PRINT OUT (AT LEAST) EVERY   1 SECONDS
-----> IDLE
-----> EMERGENCY APPLICATION
-----> BAIL OFF TO  0 P.S.I. IN BRAKE CYLINDER
-----> CONTINUE UNTIL SPEED REACHES   0 M.P.H.
>>>>>>>>>>>>>>>> TRAIN STARTING AT-1.30% GRADE
 0: 0: 0   38.800  80  20+IDLE     0 EMG REL  80#  0#    2:10  .09:10   0   14      1  LOCOMOTIVE      0 KIPS      0 KIPS   0.00
           38.814                 80#  0#                    2  LOCOMOTIVE      0 KIPS      1 KIPS   0.00
           39.580                 80#  0#                   74  BOX             0 KIPS      0 KIPS   0.00
 0: 0: 1   38.794  80  20+IDLE     0 EMG REL   0#  0#    2:3   .09:10   0   14      1  LOCOMOTIVE      0 KIPS      1 KIPS   0.00
           38.808                  0#  0#                    2  LOCOMOTIVE      1 KIPS      2 KIPS   0.00
           39.575                 80#  0#                   74  BOX             0 KIPS      0 KIPS   0.00
(((((((((((  TRAIN ENTERING  -9 DEGREE 42 MINUTE CURVE
 0: 0: 2   38.789  80  20+IDLE     0 EMG REL   0#  0#    7:16  .25:1    0   11      1  LOCOMOTIVE      0 KIPS      2 KIPS   0.25
           38.802                  0#  0#                    2  LOCOMOTIVE      2 KIPS      5 KIPS   0.00
           39.569                 80#  0#                   74  BOX             0 KIPS      0 KIPS   0.00
 0: 0: 3   38.783  80  21+IDLE     0 EMG REL   0#  0#  -30:20  .25:1    0    6      1  LOCOMOTIVE      0 KIPS      3 KIPS   0.25
           38.797                  0#  0#                    2  LOCOMOTIVE      3 KIPS      8 KIPS   0.01
           39.563                 80#  0#                   74  BOX            -2 KIPS      0 KIPS   0.00
 0: 0: 4   38.777  80  21+IDLE     0 EMG REL   0#  0#  -47:17  .25:1    0    1      1  LOCOMOTIVE      0 KIPS      5 KIPS   0.25
           38.791                  0#  0#                    2  LOCOMOTIVE      5 KIPS     10 KIPS   0.25
           39.558                  0#  1#                   74  BOX            -2 KIPS      0 KIPS   0.00
 0: 0: 5   38.772  80  21-IDLE     0 EMG REL   0#  0#  -49:14  .25:1    0   -5      1  LOCOMOTIVE      0 KIPS      5 KIPS   0.25
           38.785                  0#  0#                    2  LOCOMOTIVE      5 KIPS     12 KIPS   0.25
           39.552                  0# 13#                   74  BOX            -2 KIPS      0 KIPS   0.00
 0: 0: 6   38.766  80  20-IDLE     0 EMG REL   0#  0#  -48:13  .27:2    0  -11      1  LOCOMOTIVE      0 KIPS      6 KIPS   0.25
           38.780                  0#  0#                    2  LOCOMOTIVE      6 KIPS     12 KIPS   0.27
```

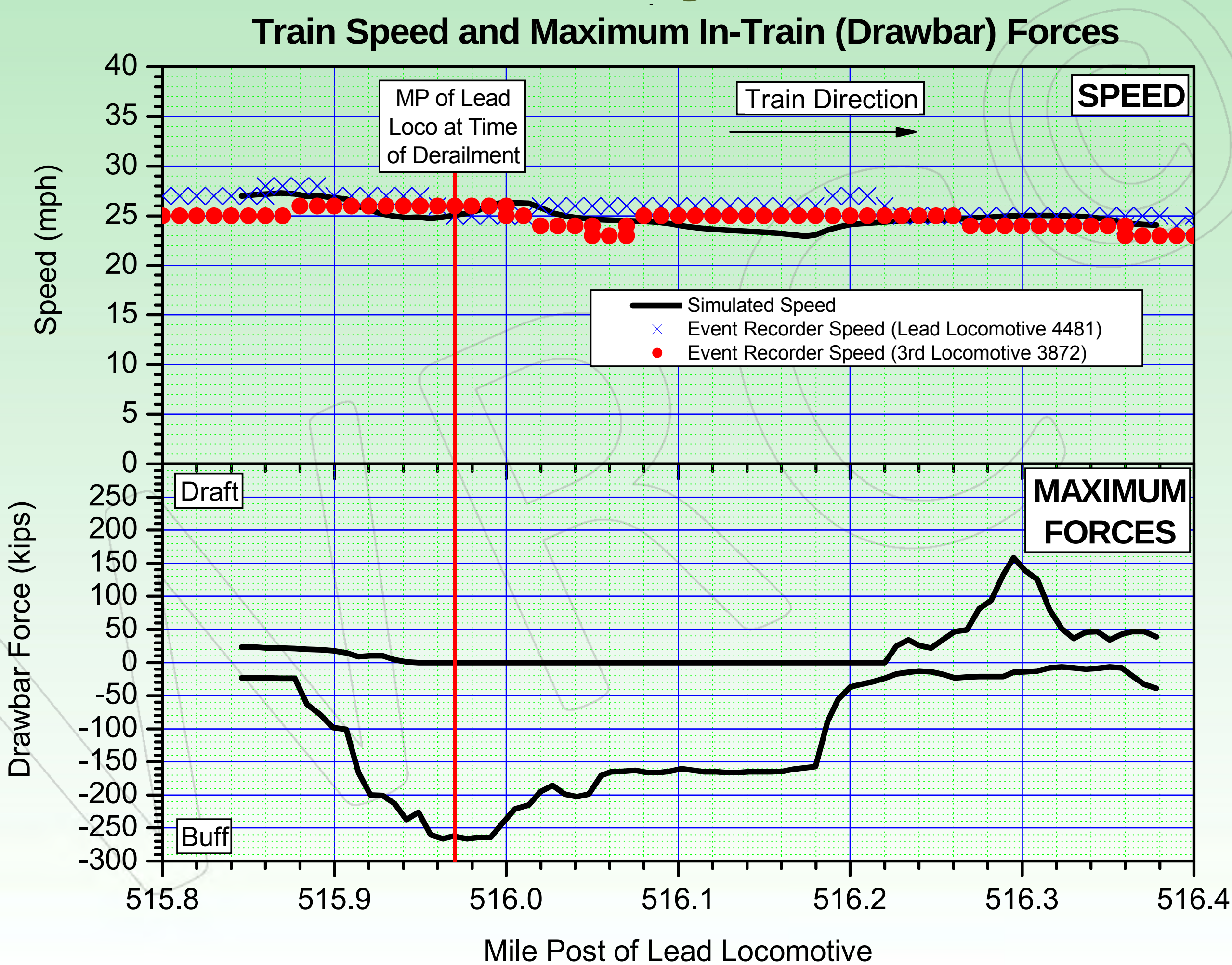
Inputs to TOS Model





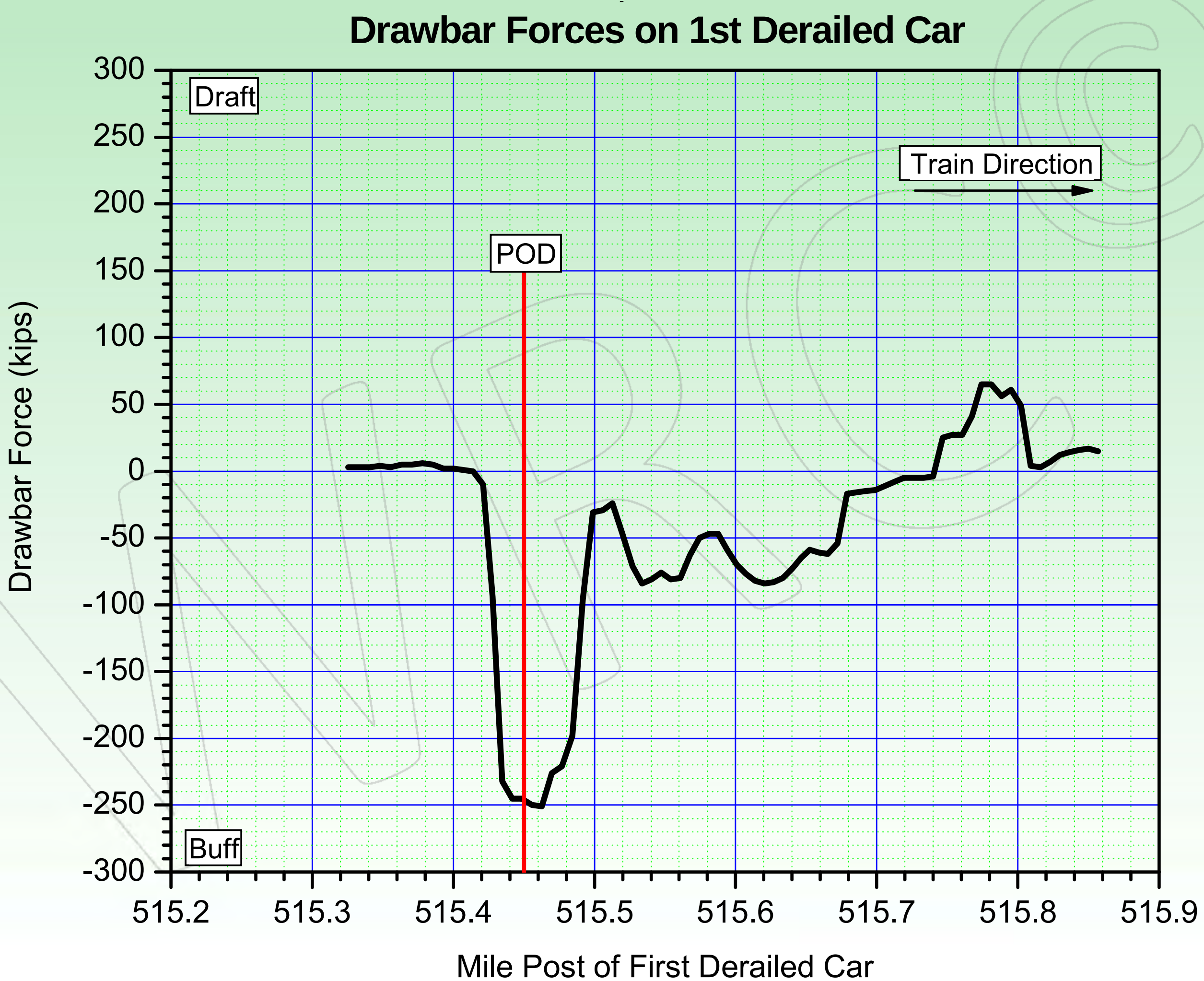
Derailment
Drawbar Forces on First Derailed Car
Drawbar Force (Kips)
250
200
150
100
50
0
-50
-100
-150
-200
-250
Train Direction
Head End Location
When Derailment Occured
MP 274.56
POD
MP 274.2
Speed (MPH)
40
35
30
25
20
15
10
5
0
Simulated Speed
Actual Speed
272.4
272.6
272.8
273.0
273.2
273.4
273.6
273.8
274.0
274.2
274.4
274.6
Milepost of Lead Locomotive

Analysis



Train Speed and Maximum In-Train (Drawbar) Forces
MP of Lead Loco at Time of Derailment
Train Direction
SPEED
Simulated Speed
Event Recorder Speed (Lead Locomotive 4481)
Event Recorder Speed (3rd Locomotive 3872)
Speed (mph)
40
35
30
25
20
15
10
5
0
Draft
Buff
MAXIMUM FORCES
Drawbar Force (kips)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
515.8
515.9
516.0
516.1
516.2
516.3
516.4
Mile Post of Lead Locomotive

TOS Analysis



TOES™

- Similar to TOS; designed by AAR/TTCI in the late 80's for use on PC's
- Written in C+
- Can Model EOC Cushion Devices
- Different Brake Pipe Model based on fluid dynamics
- Can Model Slackless Articulated Connections
- Can model more than 2 locomotive Positions
- Can model collisions (g's)

TOES Track Input Data

STARTING FOOTAGE: 1642238.4 AT HEADING(deg):= 0.00

MARKER	FOOTAGE	CURVE	SP_ELV	ELEVTN	%GRADE	SPEED	LUB	MILEPOST	STATION
'TRKBGN '	1642238.4	0.00	0.000	243.0	0.00	80.00	'N'	' 311.03'	' '
'CRV-TS '	1642238.4	0.00	0.000	243.0	0.00	80.00	'N'	' '	' '
'CRV-SC '	1642238.4	3.05	0.000	243.0	0.00	80.00	'N'	' '	' '
'ELVATN '	1642766.4	3.05	0.000	243.0	-0.50	80.00	'N'	' '	' '
'CRV-CS '	1644403.2	3.05	0.000	234.8	-0.50	80.00	'N'	' '	' '
'CRV-ST '	1644403.2	0.00	0.000	234.8	-0.50	80.00	'N'	' '	' '
'ELVATN '	1647148.8	0.00	0.000	221.1	-0.26	80.00	'N'	' '	' '
'CRV-TS '	1647360.0	0.00	0.000	220.5	-0.26	80.00	'N'	' '	' '
'CRV-SC '	1647360.0	1.00	0.000	220.5	-0.26	80.00	'N'	' '	' '
'ELVATN '	1647571.2	1.00	0.000	220.0	-0.45	80.00	'N'	' '	' '
'ELVATN '	1648468.8	1.00	0.000	216.0	-0.05	80.00	'N'	' '	' '
'ELVATN '	1650316.8	1.00	0.000	215.1	-0.11	80.00	'N'	' '	' '
'ELVATN '	1651161.6	1.00	0.000	214.2	0.30	80.00	'N'	' '	' '
'ELVATN '	1651531.2	1.00	0.000	215.3	0.54	80.00	'N'	' '	' '
'CRV-CS '	1652006.4	1.00	0.000	217.9	0.54	80.00	'N'	' '	' '
'CRV-ST '	1652006.4	0.00	0.000	217.9	0.54	80.00	'N'	' '	' '
'ELVATN '	1653537.6	0.00	0.000	226.2	0.30	80.00	'N'	' '	' '
'CRV-TS '	1653960.0	0.00	0.000	227.4	0.30	80.00	'N'	' '	' '
'CRV-SC '	1653960.0	2.33	0.000	227.4	0.30	80.00	'N'	' '	' '
'ELVATN '	1654857.6	2.33	0.000	230.1	-0.42	80.00	'N'	' '	' '
'ELVATN '	1655544.0	2.33	0.000	227.2	0.00	80.00	'N'	' '	' '
'CRV-CS '	1656283.2	2.33	0.000	227.2	0.00	80.00	'N'	' '	' '
'CRV-ST '	1656283.2	0.00	0.000	227.2	0.00	80.00	'N'	' '	' '
'ELVATN '	1656283.2	0.00	0.000	227.2	-0.12	80.00	'N'	' '	' '
'ELVATN '	1657867.2	0.00	0.000	225.3	0.00	80.00	'N'	' '	' '
'CRV-TS '	1658131.2	0.00	0.000	225.3	0.00	80.00	'N'	' '	' '
'CRV-SC '	1658131.2	1.50	0.000	225.3	0.00	80.00	'N'	' '	' '
'ELVATN '	1658606.4	1.50	0.000	225.3	-0.09	80.00	'N'	' '	' '
'CRV-CS '	1660560.0	1.50	0.000	223.5	-0.09	80.00	'N'	' '	' '
'CRV-ST '	1660560.0	0.00	0.000	223.5	-0.09	80.00	'N'	' '	' '
'ELVATN '	1663200.0	0.00	0.000	221.1	-0.09	80.00	'N'	' '	' '
'ELVATN '	1666790.4	0.00	0.000	217.9	0.00	80.00	'N'	' '	' '

```
RECTYP = 'PLATFORM'
 &END
 &PLATFM
        PLATID = 'SD40-2', DESC = 'PLATFORM ID FIELD',
        AIRDVF = 0.09, DESC = 'DAVIS AERODYNAMIC FOR PLATFORM A-END',
        AIRDVR = 0.09, DESC = 'DAVIS AERODYNAMIC FOR PLATFORM B-END',
        KSTIFF = 140000., DESC = 'PLATFORM LONGITUDINAL STIFFNESS (LBS/IN)',
        LENS2S = 68.83, DESC = 'LENGTH STRIKER TO STRIKER (FT)',
        PLTWGT = 287030., DESC = 'PLATFORM **ONLY** EMPTY WEIGHT (LBS)',
        HEMCG  = 72., DESC = 'CENTER OF GRAVITY HEIGHT (EMPTY) (IN)',
        HLDCG  = 72., DESC = 'CENTER OF GRAVITY HEIGHT (FULLY LOADED) (IN)',

PLATID = 'AUTORACK', DESC = 'PLATFORM ID FIELD',
        AIRDVF = 0.0853, DESC = 'DAVIS AERODYNAMIC FOR PLATFORM A-END',
        AIRDVR = 0.0853, DESC = 'DAVIS AERODYNAMIC FOR PLATFORM B-END',
        KSTIFF = 140000., DESC = 'PLATFORM LONGITUDINAL STIFFNESS (LBS/IN)',
        LENS2S = 94.7, DESC = 'LENGTH STRIKER TO STRIKER (FT)',
        PLTWGT = 29356., DESC = 'PLATFORM **ONLY** EMPTY WEIGHT (LBS)',
        HEMCG  = 72., DESC = 'CENTER OF GRAVITY HEIGHT (EMPTY) (IN)',
        HLDCG  = 72., DESC = 'CENTER OF GRAVITY HEIGHT (FULLY LOADED) (IN)',
```

```
FUELID = 'SD60', DESC = 'PLATFORM ID FIELD',
      LWIDGL = 2.9, DESC = 'GAL/HOUR LOW IDLE',
      HGIDGL = 2.9, DESC = 'GAL/HOUR HIGH IDLE',
      R1GAL  = 11.7, DESC = 'GAL/HOUR RUN 1',
      R2GAL  = 22.6, DESC = 'GAL/HOUR RUN 2',
      R3GAL  = 47.8, DESC = 'GAL/HOUR RUN 3',
      R4GAL  = 65.2, DESC = 'GAL/HOUR RUN 4',
      R5GAL  = 87.4, DESC = 'GAL/HOUR RUN 5',
      R6GAL  = 133.7, DESC = 'GAL/HOUR RUN 6',
      R7GAL  = 158.89999, DESC = 'GAL/HOUR RUN 7',
      R8GAL  = 186., DESC = 'GAL/HOUR RUN 8',
      DYNGAL = 10.4, DESC = 'GAL/HOUR DYNAMIC',
```

```
&END
 &COUPLR
        CPLRID = 'LONG1', DESC = 'COUPLER ID FIELD',
        CPRLEN = 60., DESC = 'COUPLER LENSTR (IN)',
        KNUTYP = 'E', DESC = 'E, F, OR H KNUCKLE',
        CPRANG = 12.75, DESC = 'COUPLER ANGLE
(DEGREES)',
        FRESLK = 0.5, DESC = 'FREE SLACK (IN)',
        ISALN  = F, DESC = 'TRUE IF ALIGNMENT CONTROL,
ELSE FALSE',
```

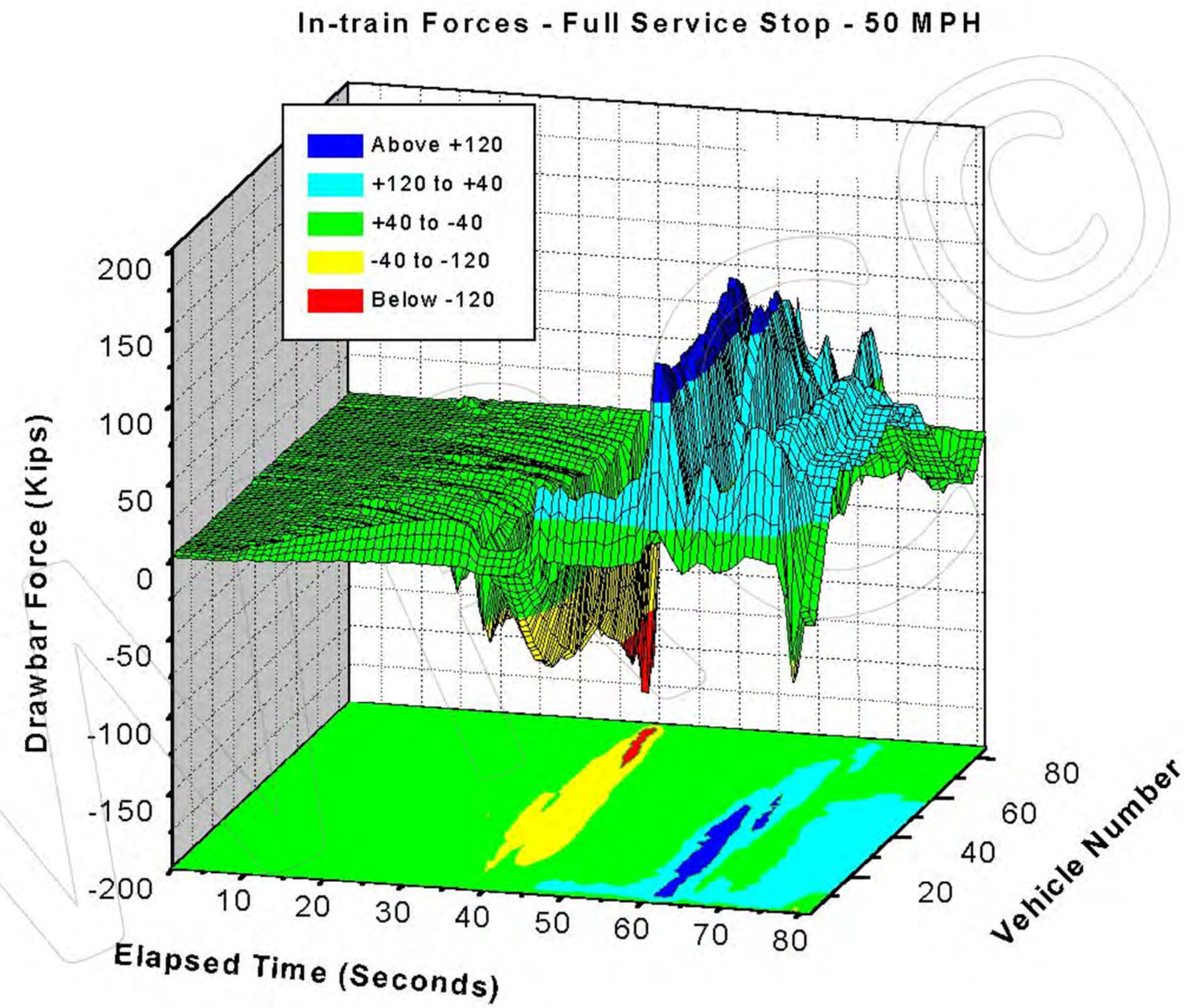
TOES Consist Input Data

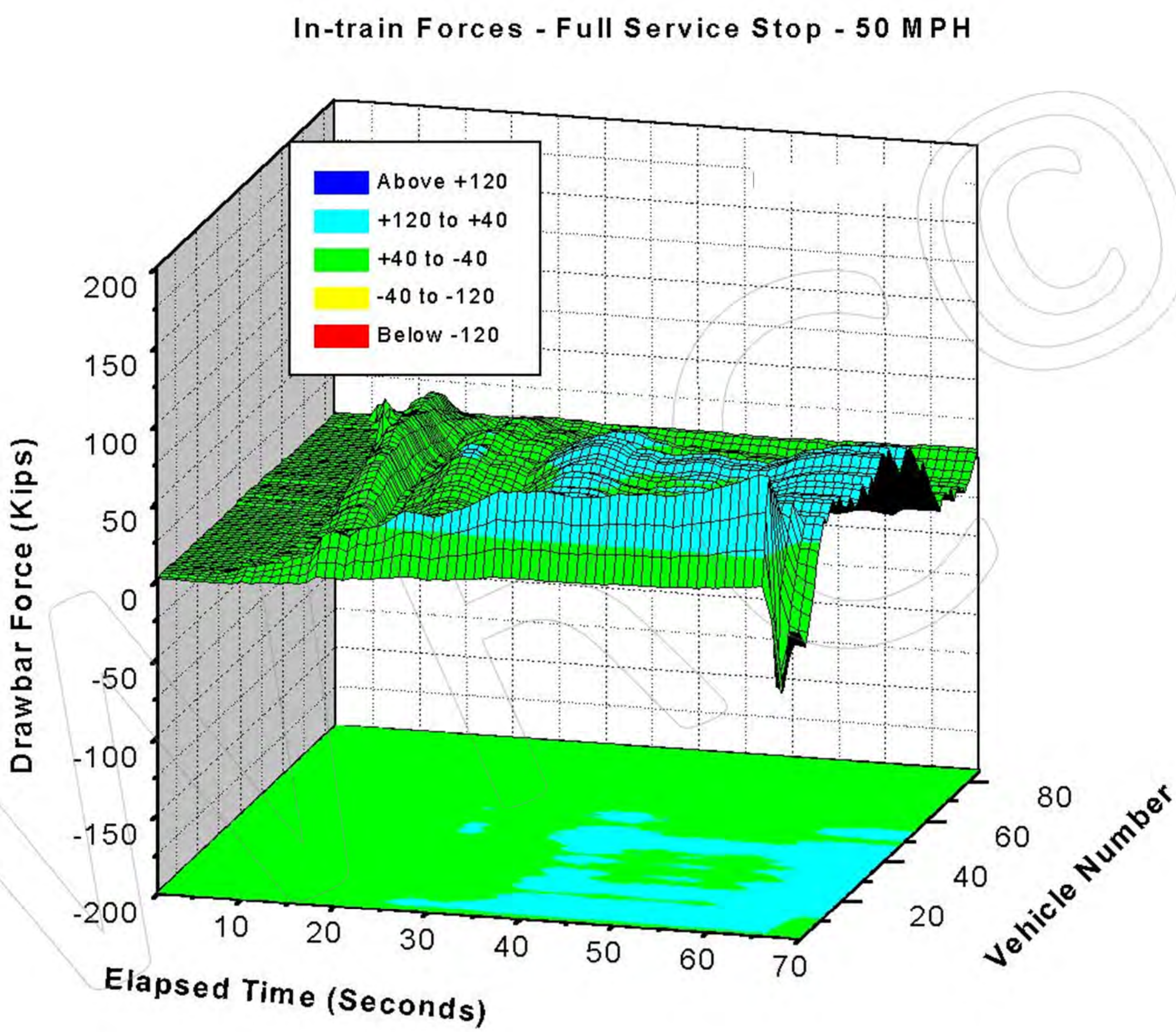
TOES Command File Data

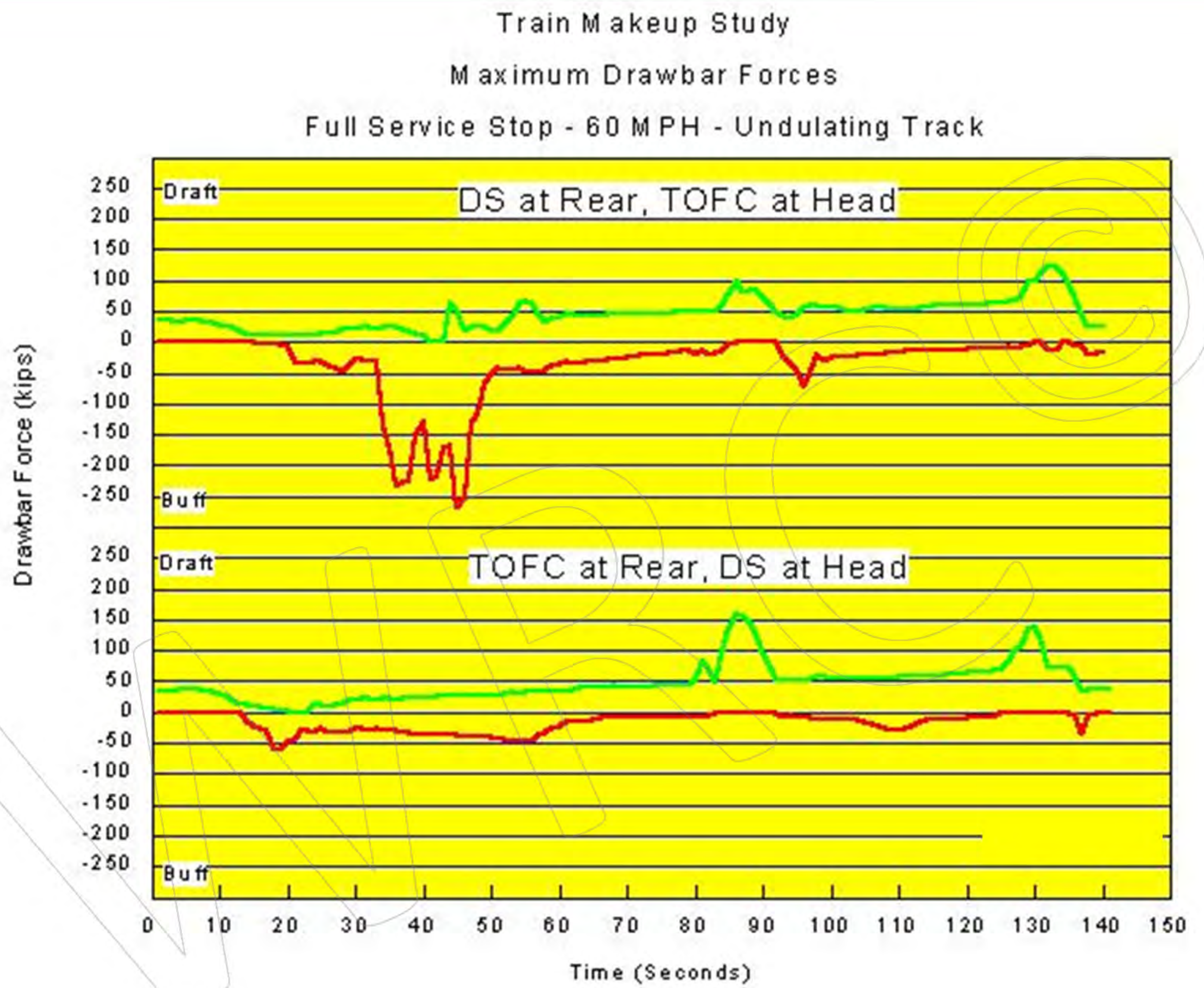
```
BRAKE PIPE_PRESSURE 90.
SWITCH ON POST_PROCESSOR
FORWARD_DIRECTION INCREASING_FOOTAGE FORWARD
COM OUTPUT ALL_LOCOMOTIVES ON

ISOLATE THROTTLE START_STOP_ISOLATE 3 6
ISOLATE THROTTLE START_STOP_ISOLATE 8 9
ISOLATE DYNAMIC START_STOP_ISOLATE 3 6
ISOLATE DYNAMIC START_STOP_ISOLATE 8 9

PILOT_VALVE CUT_OUT 1 LAST_THROTTLE
MU2A_VALVE CUT_OUT 1 LAST_THROTTLE

OUTPUT EVERY 1 ON

RUN 4
START 23 1681415 INCREASING_FOOTAGE FIRST_RECORD
CON 10 S

UNDESIRED_EMERGENCY 21
CON 1 S
BAIL 0

CON 1 S

UNDESIRED_EMERGENCY 101
CON 5 SECONDS

RUN 3
CON 3 SECONDS

IDLE
CON 0 MPH 999 SECONDS

CON 10 S

STOP
```

TOES Output File Data

```
ISOLATE DYNAMIC START_STOP_ISOLATE    8   9
 PILOT_VALVE CUT_OUT    FROM THROTTLE   1 TO LAST_THROTTLE
 MU2A_VALVE CUT_OUT    FROM THROTTLE   1 TO LAST_THROTTLE
 OUTPUT EVERY   1 ON
 RUN  4 [LOCOMOTIVE NUMBER    1]
 RUN  4 [LOCOMOTIVE NUMBER    2]
 IDLE [LOCOMOTIVE NUMBER   3]
 IDLE [LOCOMOTIVE NUMBER   4]
 IDLE [LOCOMOTIVE NUMBER   5]
 IDLE [LOCOMOTIVE NUMBER   6]
 RUN  4 [LOCOMOTIVE NUMBER    7]
 IDLE [LOCOMOTIVE NUMBER   8]
 IDLE [LOCOMOTIVE NUMBER   9]
 RUN  4 [LOCOMOTIVE NUMBER   10]
 SPEED SPECIFIED AT      23.00 MPH
 HEAD OF TRAIN FOOTAGE SPECIFIED AT       1681415.0
 GENERAL TRAIN DIRECTION SPECIFIED IN INCREASING FOOTAGE
 HEAD OF TRAIN SPECIFIED TO BE FIRST VEHICLE RECORD
 CONTINUE         10.000 SECONDS

 VEH     LOCATION   SPEED-mph ACC-mphpm GRADE CURVE NOTCH  FORE   AFT  BPP  BCP

 T: 0: 0: 0.000 [Spd-Lmt: 80]      No buff force      Max Draft/Veh: 10>  52K
 Tot Cyls:  Tr Av BCP:  Tot Loc Cyls:  Loc Av BCP:  Tot Car Cyls:  Car Av BCP:
      171        0.00            80         0.00            91         0.00
  Avg Trn Speed:  23.00    Avg Trn Accel:      4.473
   1 311.03 +39140.1   23.00S    0.00a  0.4%  0.0D RUN 4     0K   16K  90#   0#
   2 311.03 +39067.0   23.00S    0.00a  0.4%  0.0D RUN 4    16K   33K  90#   0#
   3 311.03 +38997.4   23.00S    0.00a  0.4%  0.0D ISOLAT   33K   29K  90#   0#
   4 311.03 +38929.8   23.00S    0.00a  0.4%  0.0D ISOLAT   29K   26K  90#   0#
   5 311.03 +38860.7   23.00S    0.00a  0.4%  0.0D ISOLAT   26K   23K  90#   0#
   6 311.03 +38789.6   23.00S    0.00a  0.4%  0.0D ISOLAT   23K   20K  90#   0#
   7 311.03 +38716.0   23.00S    0.00a  0.4%  0.0D RUN 4    20K   43K  90#   0#
   8 311.03 +38641.9   23.00S    0.00a  0.4%  0.0D ISOLAT   43K   40K  90#   0#
   9 311.03 +38567.7   23.00S    0.00a  0.4%  0.0D ISOLAT   40K   36K  90#   0#
  10 311.03 +38493.6   23.00S    0.00a  0.4%  0.0D RUN 4    36K   52K  90#   0#
  11 311.03 +38419.8   23.00S    0.00a  0.4%  0.0D          52K   52K  90#   0#
  12 311.03 +38354.3   23.00S    0.00a  0.4%  0.0D          52K   51K  90#   0#
  13 311.03 +38298.0   23.00S    0.00a  0.4%  0.0D          51K   50K  90#   0#
  14 311.03 +38237.9   23.00S    0.00a  0.4%  0.0D          50K   48K  90#   0#
```


In-train Forces - Full Service Stop - 50 MPH
Above +120
+120 to +40
+40 to -40
-40 to -120
Below -120
Drawbar Force (Kips)
200
150
100
50
0
-50
-100
-150
-200
10
20
30
40
50
60
70
80
Elapsed Time (Seconds)
20
40
60
80
Vehicle Number

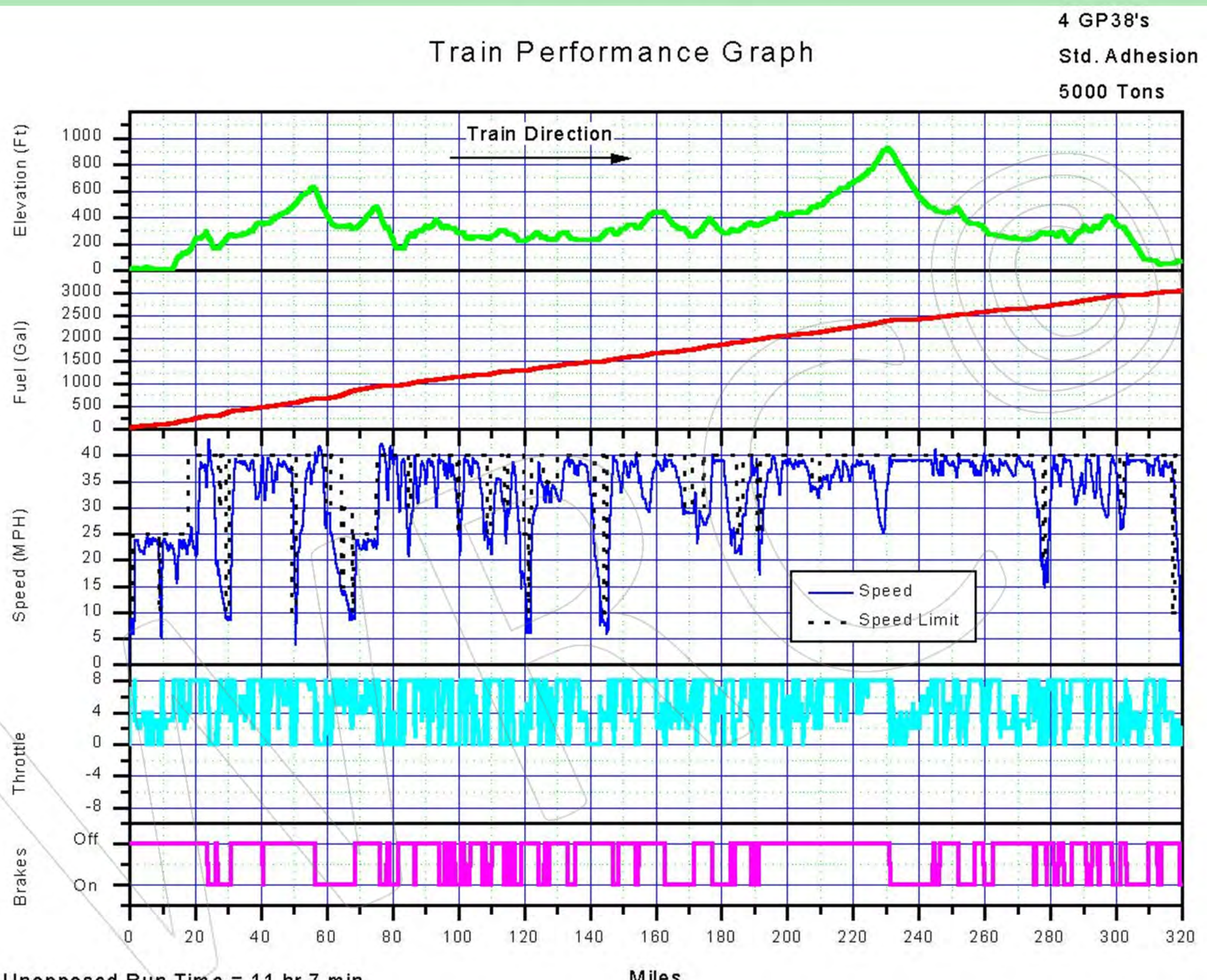

In-train Forces - Full Service Stop - 50 MPH
Above +120
+120 to +40
+40 to -40
-40 to -120
Below -120
Drawbar Force (Kips)
200
150
100
50
0
-50
-100
-150
-200
10
20
30
40
50
60
70
Elapsed Time (Seconds)
80
60
40
20
Vehicle Number



Train Makeup Study
Maximum Drawbar Forces
Full Service Stop - 60 MPH - Undulating Track
DS at Rear, TOFC at Head
TOFC at Rear, DS at Head
Draft
Buff
Drawbar Force (kips)
Time (Seconds)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Train Energy Model (TEM)

- Used for over-the-road simulation
- Useful for determining approximate speeds
- Accurate predictions of fuel consumption
- Can be used in wheel/rail lubrication studies



Unopposed Run Time = 11 hr 7 min

Fuel Consumption = 3036 Gallons

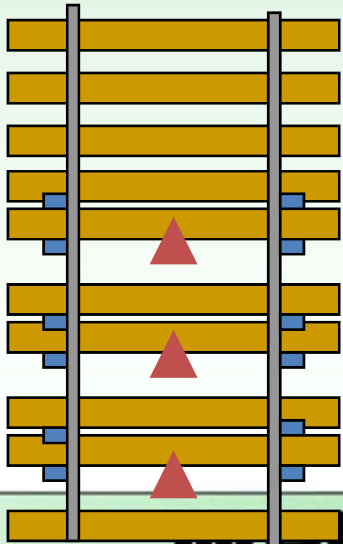
Summary of Longitudinal Models

- Accurate in predicting traction and braking forces
  - On any vehicle in the train anywhere on the track
- Accurate in predicting speed of the train
- Accurate in predicting over the road run times
- Accurate in predicting fuel consumption

Rail Anchoring - Restraint Analysis

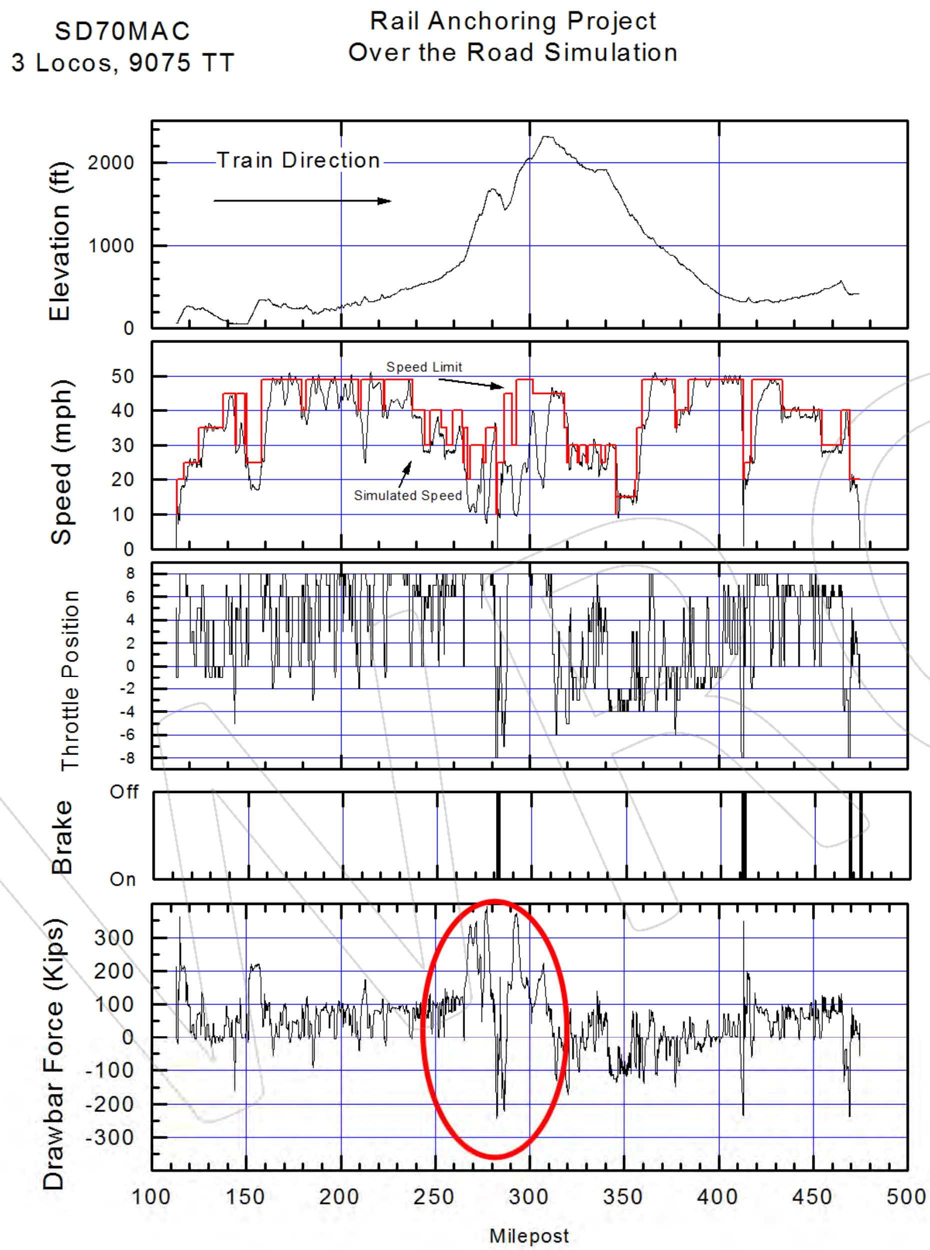
- Effect of introduction of AC's on rail anchoring
  - Will AC's accelerate joint problems such as joint batter and joint bar cracking?
  - What anchor patterns required to restrain longitudinal forces?
  - What curves/tangents should have priority for anchor upgrading?
  - Does train handling need to be restricted in certain areas?

Effect of Poor Rail Anchoring



Priority Rating for Rail Anchoring Improvements

- Determine highest areas of grade resistance
  - Track profile - grades and curvature
  - Train lengths - looking for average grade resistance under entire train - varies with different train lengths
- Determine areas of high longitudinal forces
- Prioritize based on these factors

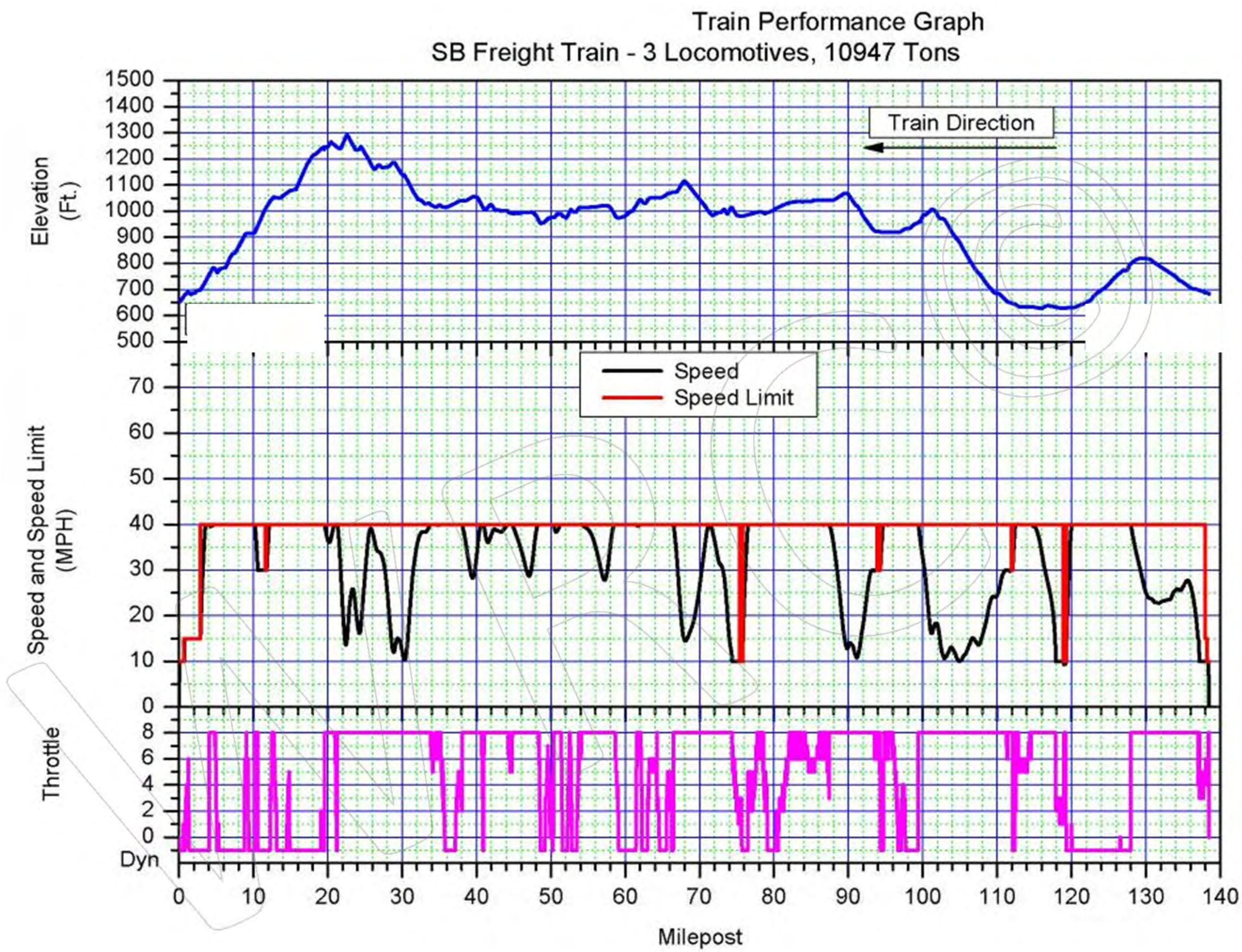


Rail Anchoring Study -

Over-The-Road Simulation

Curve Elevation Optimization

- Longitudinal modeling provides a range of actual train speeds under a variety of tonnage, power, and train operations factors (slow orders, speed restrictions, etc.)
- Issues with determining optimum elevation
  - Mixed freight and passenger
  - Heavy grade territory; uphill vs. downhill speeds
  - Distances from know speed restrictions; acceleration/deceleration
  - Different tonnage trains in same direction (drag vs. manifest/intermodal)


Train Performance Graph
SB Freight Train - 3 Locomotives, 10947 Tons
Train Direction
Elevation (Ft.)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
Speed
Speed Limit
Speed and Speed Limit (MPH)
70
60
50
40
30
20
10
0
Throttle
8
6
4
2
0
Dyn
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Milepost

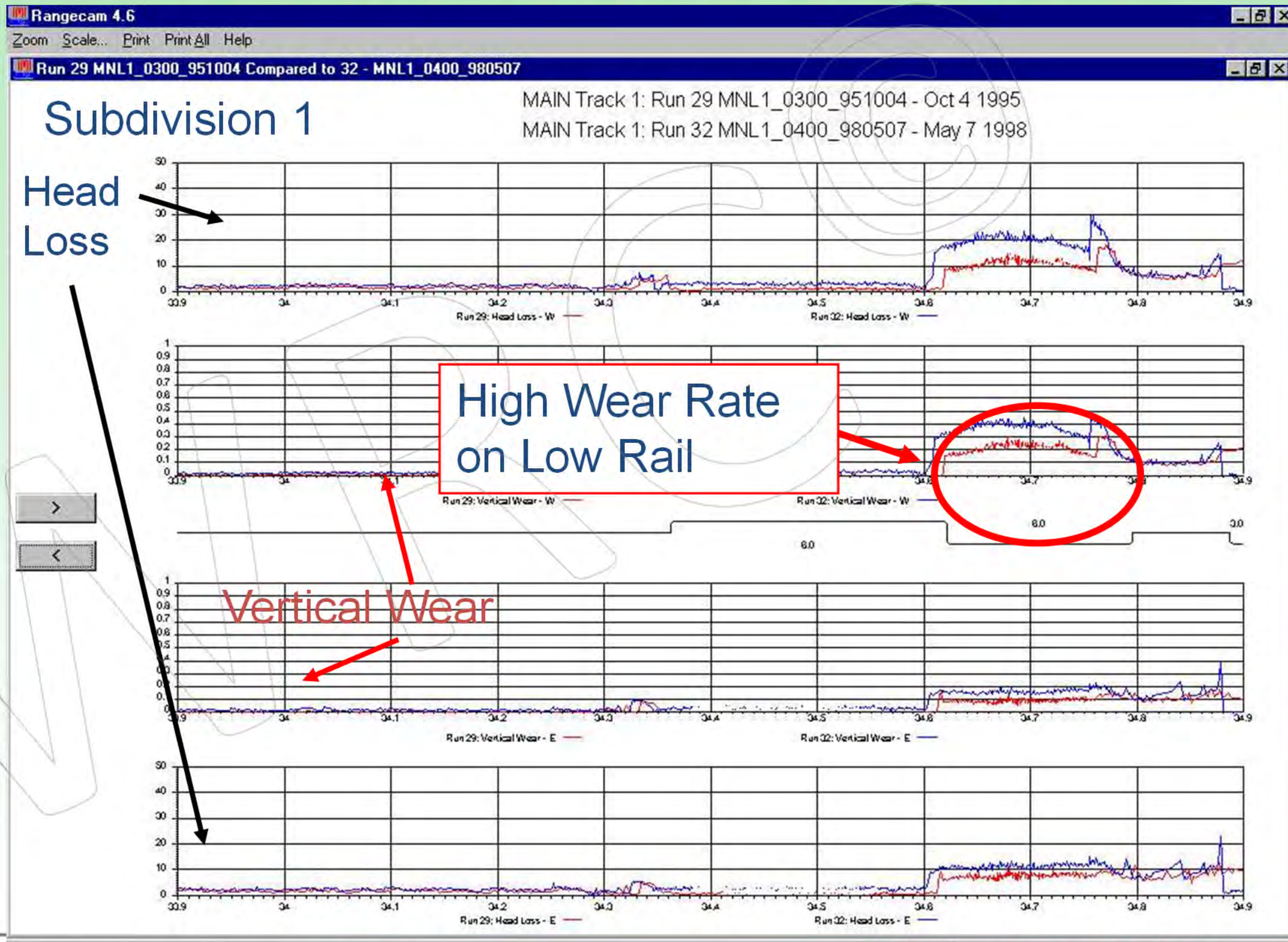
Printed 9/17/2008

							1	Under Bal		3	Over Bal		
MP	Curvature (Degrees)	Existing SE (Inches)	Freight Speed Limit (MPH)	Simulated Speed (MPH) SB Freight 6432 Tons	Speed (MPH) NB Freight 2256 Tons	Calc SE SB Freight	Calc SE NB Freight	Recom Freight SE	Existing Passenger Speed Limit (MPH)	Passenger Min Allowable SE (MPH)	Final Rec SE	Diff from Actual SE	Diff Final from Recom Freight
1.74	2.50	0.50	15.00	14.81	9.97	-0.63	-0.83	0.00	15.00	1.00	1.00	0.50	1.00
6.28	2.50	2.00	40.00	40.00	40.00	1.68	1.68	1.68	50.00	1.19	1.68	-0.32	0.00
6.80	2.00	0.80	40.00	35.00	39.97	0.64	1.14	1.14	50.00	1.00	1.14	0.34	0.00
7.28	4.00	3.75	40.00	35.00	38.46	2.28	2.96	2.96	50.00	3.70	3.70	-0.05	0.74
7.62	2.00	1.00	35.00	35.00	34.94	0.64	0.64	0.64	35.00	1.00	1.00	0.00	0.36
8.06	1.50	0.50	40.00	40.00	34.98	0.61	0.23	0.61	50.00	1.00	1.00	0.50	0.39
8.86	4.00	5.00	40.00	40.00	37.74	3.29	2.82	3.29	50.00	3.70	3.70	-1.30	0.41
9.30	3.00	3.00	40.00	40.00	39.96	2.22	2.21	2.22	50.00	2.03	2.22	-0.78	0.00
10.10	4.00	4.00	40.00	40.00	39.98	3.29	3.28	3.29	50.00	3.70	3.70	-0.30	0.41
11.00	4.00	4.00	40.00	40.00	39.96	3.29	3.28	3.29	50.00	3.70	3.70	-0.30	0.41
11.34	4.00	3.50	40.00	40.00	39.96	3.29	3.28	3.29	50.00	3.70	3.70	0.20	0.41
11.64	4.10	4.00	40.00	40.00	39.91	3.40	3.38	3.40	50.00	3.87	3.87	-0.13	0.47
12.15	1.33	0.50	40.00	40.00	39.97	0.43	0.42	0.43	50.00	1.00	1.00	0.50	0.57
13.21	4.00	4.00	40.00	33.15	39.99	1.95	3.29	3.29	50.00	3.70	3.70	-0.30	0.41
13.52	4.00	4.50	40.00	30.00	39.98	1.41	3.28	3.28	50.00	3.70	3.70	-0.80	0.42
13.77	4.00	4.00	40.00	30.00	37.55	1.41	2.78	2.78	50.00	3.70	3.70	-0.30	0.92
14.29	4.00	4.50	30.00	25.00	29.96	0.68	1.41	1.41	30.00	1.00	1.41	-3.09	0.00
14.59	4.00	4.00	30.00	25.00	28.84	0.68	1.23	1.23	30.00	1.00	1.23	-2.77	0.00
14.80	3.50	1.00	25.00	25.00	24.63	0.47	0.42	0.47	25.00	1.00	1.00	0.00	0.53
14.86	3.50	1.00	25.00	25.00	25.00	0.47	0.47	0.47	25.00	1.00	1.00	0.00	0.53
15.09	4.00	2.00	25.00	25.00	24.94	0.68	0.67	0.68	25.00	1.00	1.00	-1.00	0.33
15.30	4.00	5.50	40.00	29.00	25.00	1.25	0.68	1.25	50.00	3.70	3.70	-1.80	2.45
15.66	4.00	4.00	40.00	39.38	25.00	3.16	0.68	3.16	50.00	3.70	3.70	-0.30	0.54
16.40	2.00	2.50	40.00	40.00	34.59	1.14	0.60	1.14	50.00	1.00	1.14	-1.36	0.00
17.18	2.90	4.00	40.00	40.00	39.99	2.11	2.11	2.11	50.00	1.86	2.11	-1.89	0.00
17.46	3.00	4.00	40.00	40.00	39.95	2.22	2.21	2.22	50.00	2.03	2.22	-1.78	0.00
18.00	4.00	4.00	40.00	40.00	39.97	3.29	3.28	3.29	50.00	3.70	3.70	-0.30	0.41
18.24	4.10	4.00	40.00	40.00	39.95	3.40	3.38	3.40	50.00	3.87	3.87	-0.13	0.47
18.84	4.00	4.00	40.00	40.00	39.99	3.29	3.29	3.29	50.00	3.70	3.70	-0.30	0.41
19.14	4.10	4.00	40.00	40.00	39.99	3.40	3.39	3.40	50.00	3.87	3.87	-0.13	0.47
19.38	4.00	4.00	40.00	40.00	40.00	3.29	3.29	3.29	50.00	3.70	3.70	-0.30	0.41

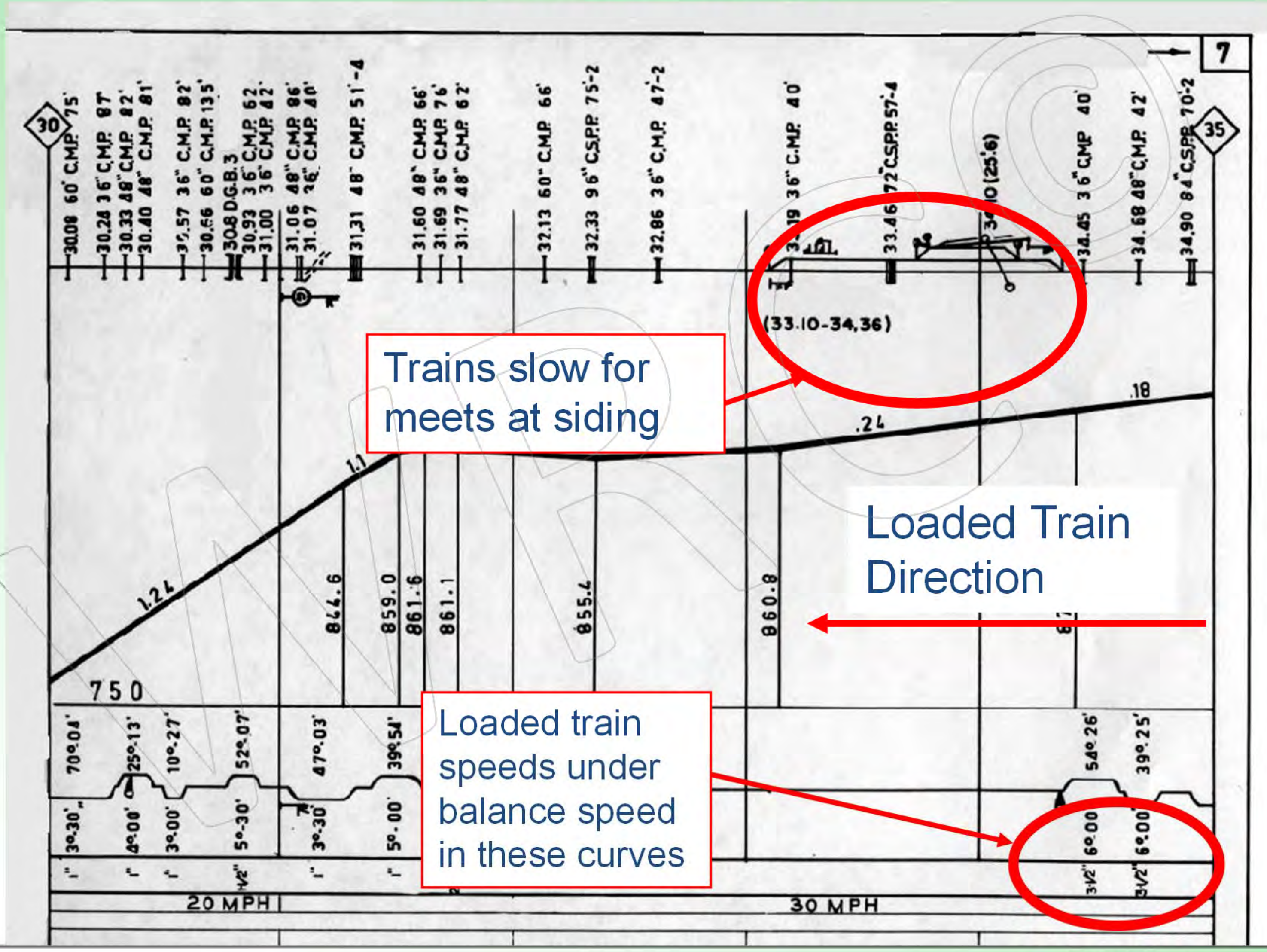
Second Case

- High rail wear rate on low rail in 6 degree curve at location of heavily used siding switch.
- Many loaded trains slowing to enter siding at 10-15 MPH.
- Curve balanced for 30 MPH operation with 2.75” elevation

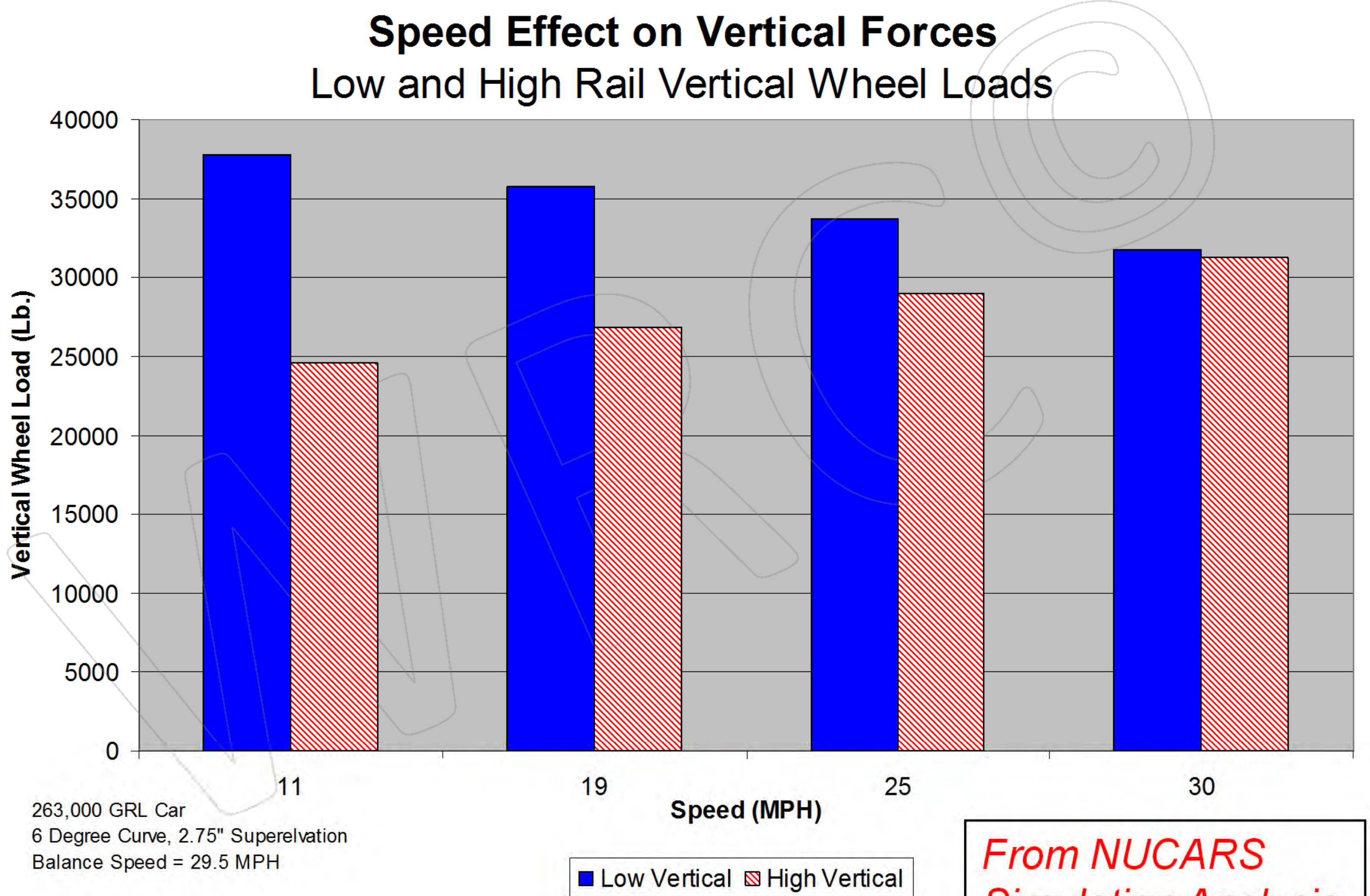
Increased Rail Wear due to Operational Factors



Track Profile

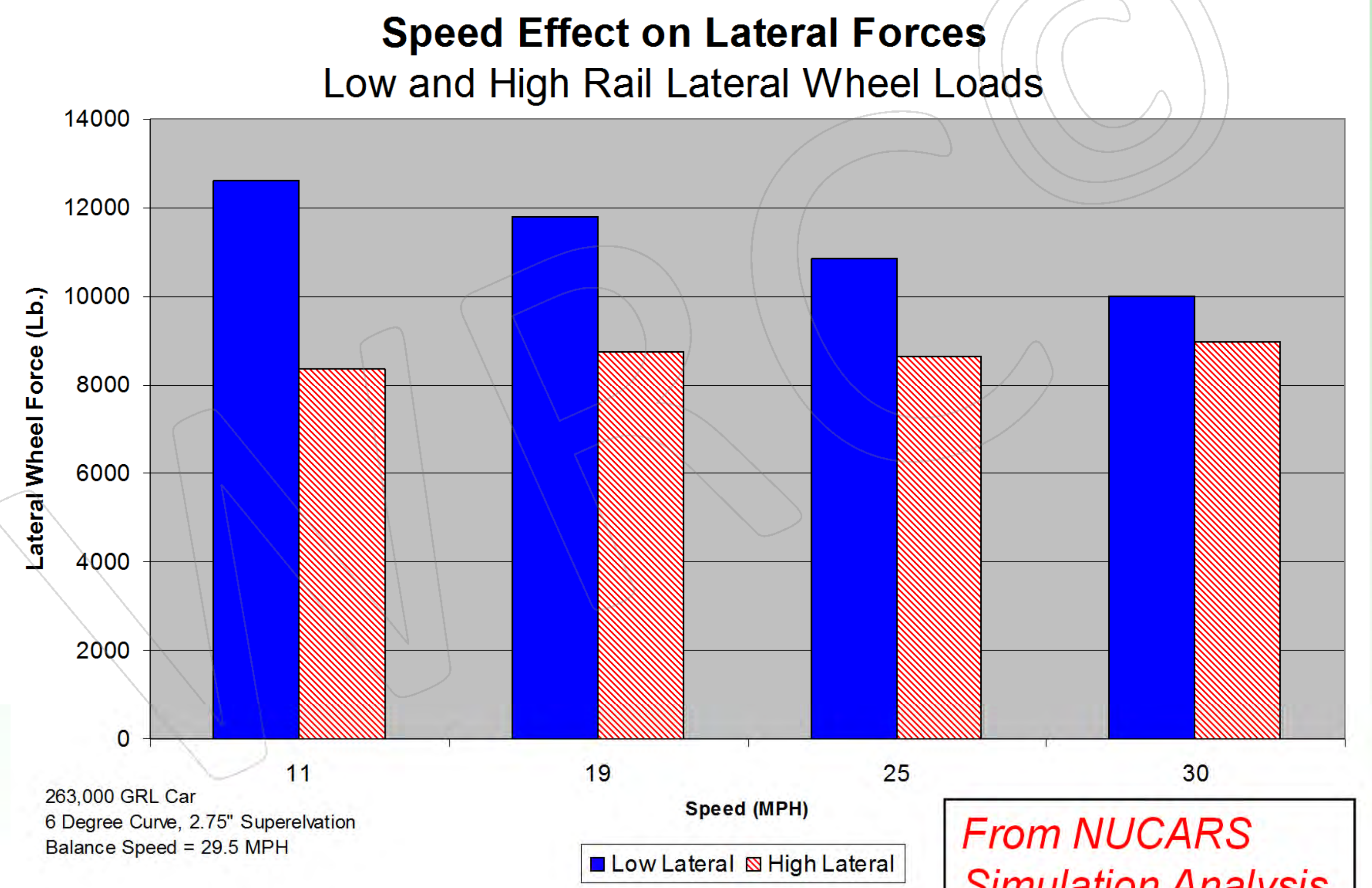


Effect of Operating Speed on Wheel Loading



From NUCARS Simulation Analysis

Effect of Speed on Lateral Forces



From NUCARS Simulation Analysis

Possible Solution

El. Eq. = .00067 (6) (15 x15)

= 0.90 inch call it ~ 1.0 inch

For speeds entering siding between 10-15 MPH, an elevation of 1.0 inch would be more appropriate.

Vehicle Dynamics Models

- Generally used to model one vehicle operating over a section of track (1000 ft. typical)
- Can simulate multiple types of car defects or wear
- Can simulate multiple types of rail geometry perturbations
- Can simulate at any speed
- Can predict wheelset lateral, vertical forces and L/V ratios (At a minimum)
- Generally called MBS (Multi-Body Simulation) models

Leading MBS Simulation Models

- VAMPIRE
  - Developed by British Rail Starting in 1970s
  - Now managed by Delta Rail of Derby England
- NUCARS™
  - Developed by AAR/TTCI in mid 1980's
  - First release 1987, many revisions since
- SIMPACK
  - Developed in Germany as MBS package at German Aerospace Research (DLR)
  - In 1995 first release with rail version; Siemens involved in effort
  - Claims to do vehicle dynamics and train dynamics

Leading MBS Simulation Models

- ADAMS Rail
  - Started with MBS software MSC.ADAMS as platform
  - In 1993 Dutch Rail began effort to customize for rail applications
  - In 1996, MEDYNAs development team joined up with MSC.ADAMS/RAIL
  - Now Marketed by MSC Software
- Universal Mechanism (UM)
  - Developed as MBS open platform by Laboratory of Computational Mechanics
    Bryansk State Technical University, Russia
  - Has Rail capabilities, claims to do vehicle and train dynamics
- GENSYS
  - Started in Sweden in 1980's with ASEA
  - In 1992 full MBS version released for rail vehicles

University of Manchester Benchmark

- Completed ~1998
- Compared NUCARS, VAMPIRE, ADAMS RAIL, GENSYS, SIMPACK
- In general, all models were in close agreement on predicting wheel/rail forces
- NUCARS and VAMPIRE had fastest run times

How can MBS modeling help in the wheel/rail environment?

- Optimize wheel profiles
- Optimize turnout design
- Optimize rail profiles; rail grinding strategies
- Optimize curve elevation
- Study rail lubrication strategies and quantify benefits
- Study wheel and rail wear under various regimes
- Analyze RCF issues
- Study derailments and contributions from various factors
- Acoustic Modeling

Vehicle Dynamics Models

- Car Conditions
  - Springs
  - Side Bearings
    - ✓ Constant Contact
    - ✓ Standard roller
  - Damping Levels
    - ✓ Friction wedges
    - ✓ Hydraulic
  - Wheel Profiles
  - Car center of gravity
  - Centerplate conditions
  - Steering linkages
  - Bump stops

Vehicle Dynamics Models Con't.

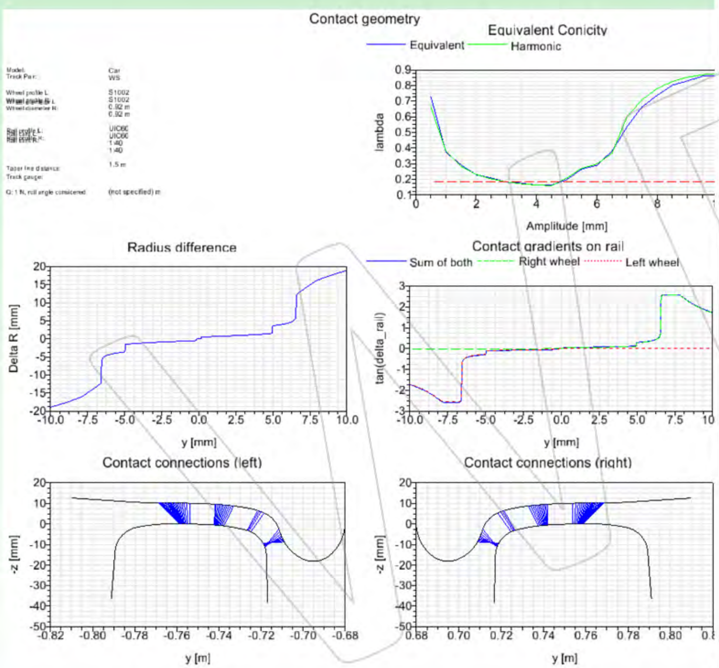
- Track Conditions
  - Crosslevel
  - Gage
  - Alignment
  - Rail Profile
  - Rail Lubrication
    - Gage face and top of rail
- Operating Conditions
  - Speed

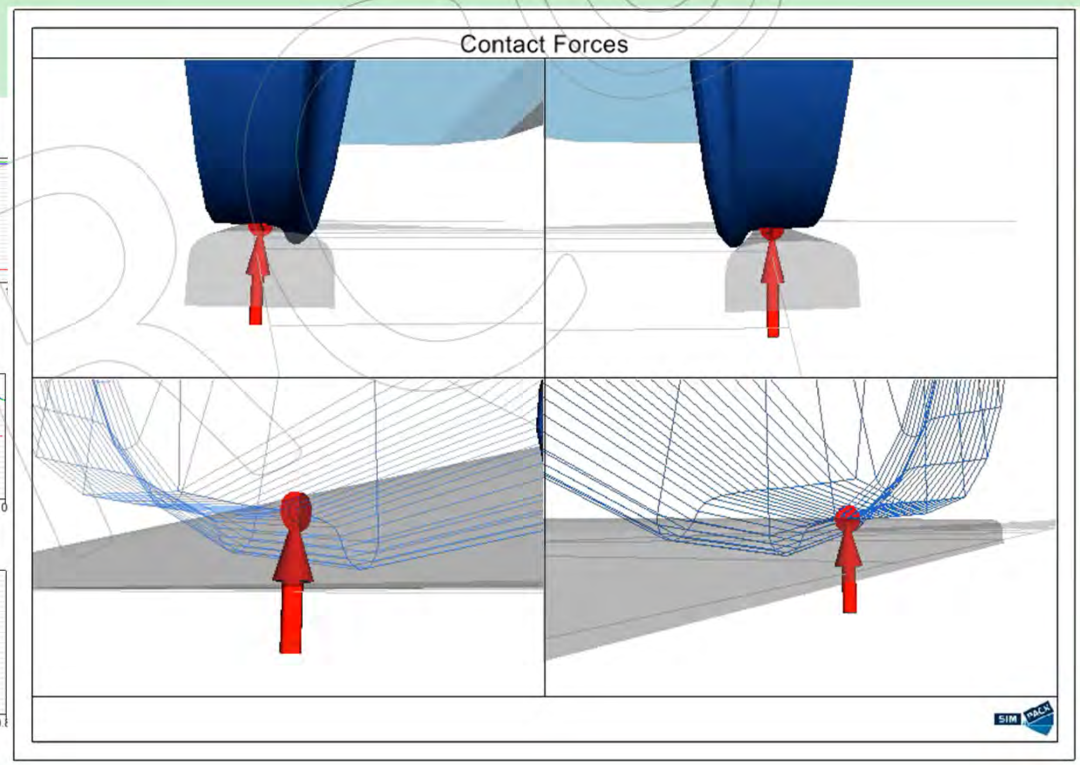
Vehicle Dynamics Models Con't

- <u>Outputs</u>
  - Vertical Wheel Forces
  - Lateral Wheel Forces
  - L/V ratios
  - Accelerations
  - Displacements of springs, dampers, side bearings
  - Wheelset position
  - Transducers anywhere on car

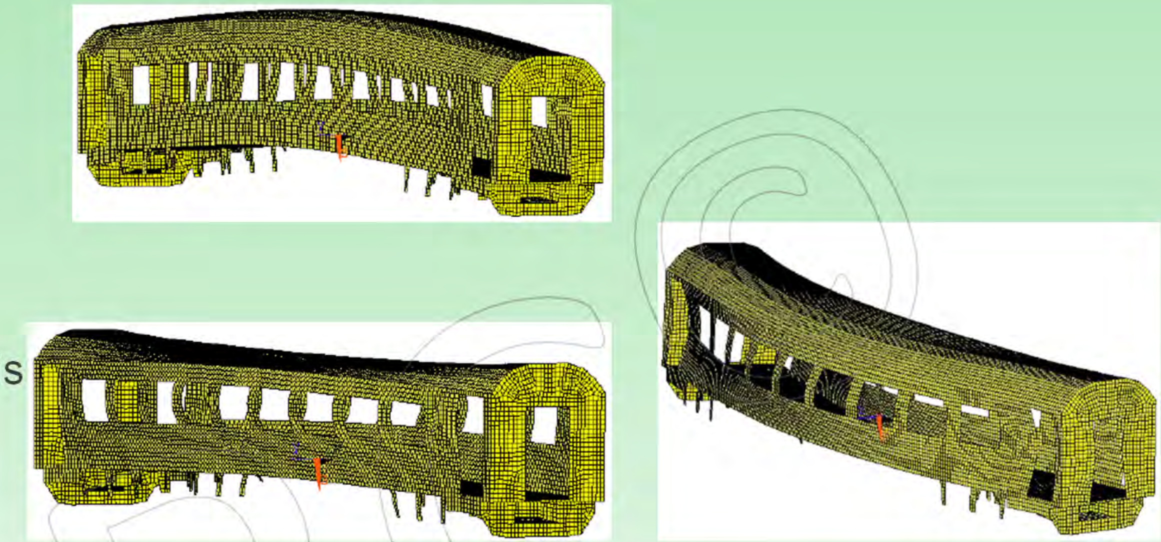
Rail-to-Wheel Contact

- Arbitrary number of contact patches
- Each wheel considered separately
- Profiles from library or measured
- Variable friction coefficient





Flexible Bodies



Mängel/Hecht, SIMPACK User Meeting 2011

Flexible carbody

- Passenger comfort analysis

Flexible bogie frame

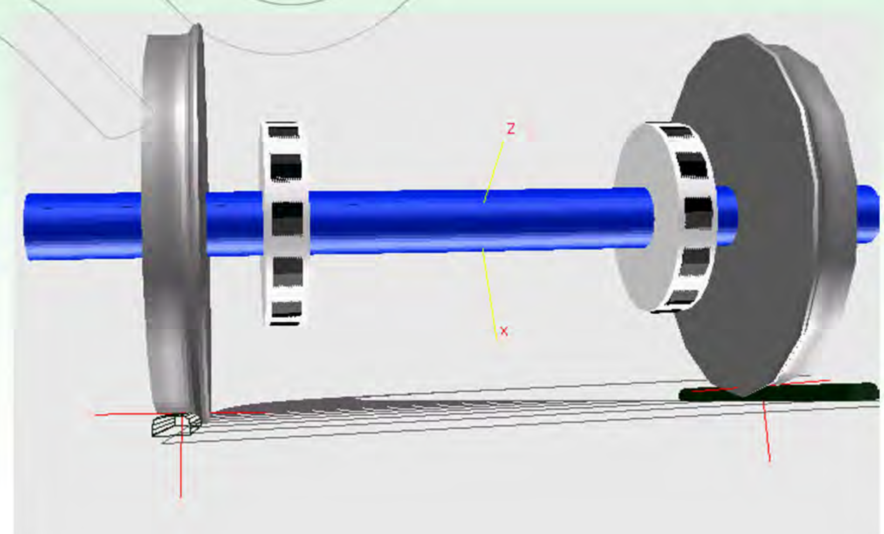
- Derailment tests
- Durability

Flexible wheelsets

- Drivetrain analysis
- Durability

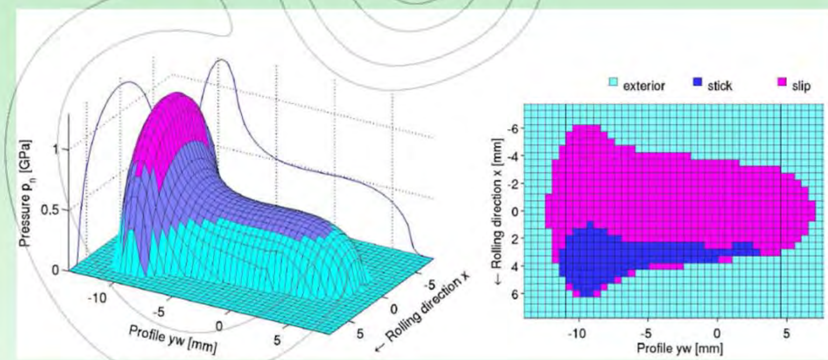
FE Interfaces

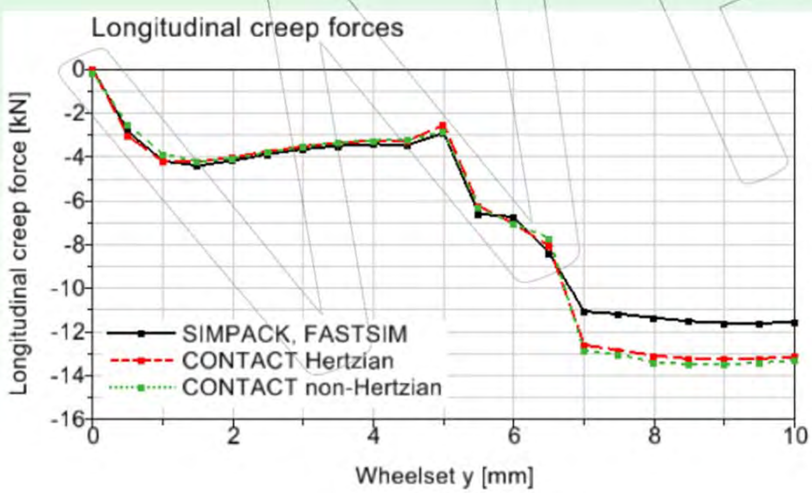
- ANSYS, NASTRAN, Abaqus, …

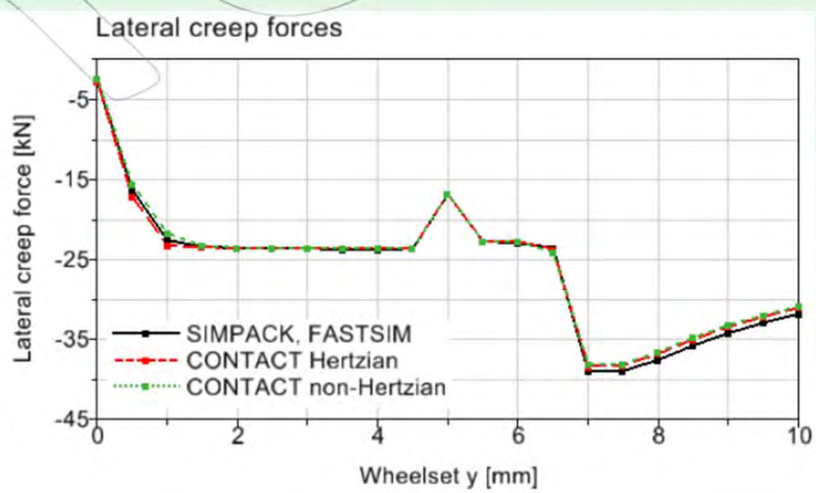


SIMPACK Kalker Contact

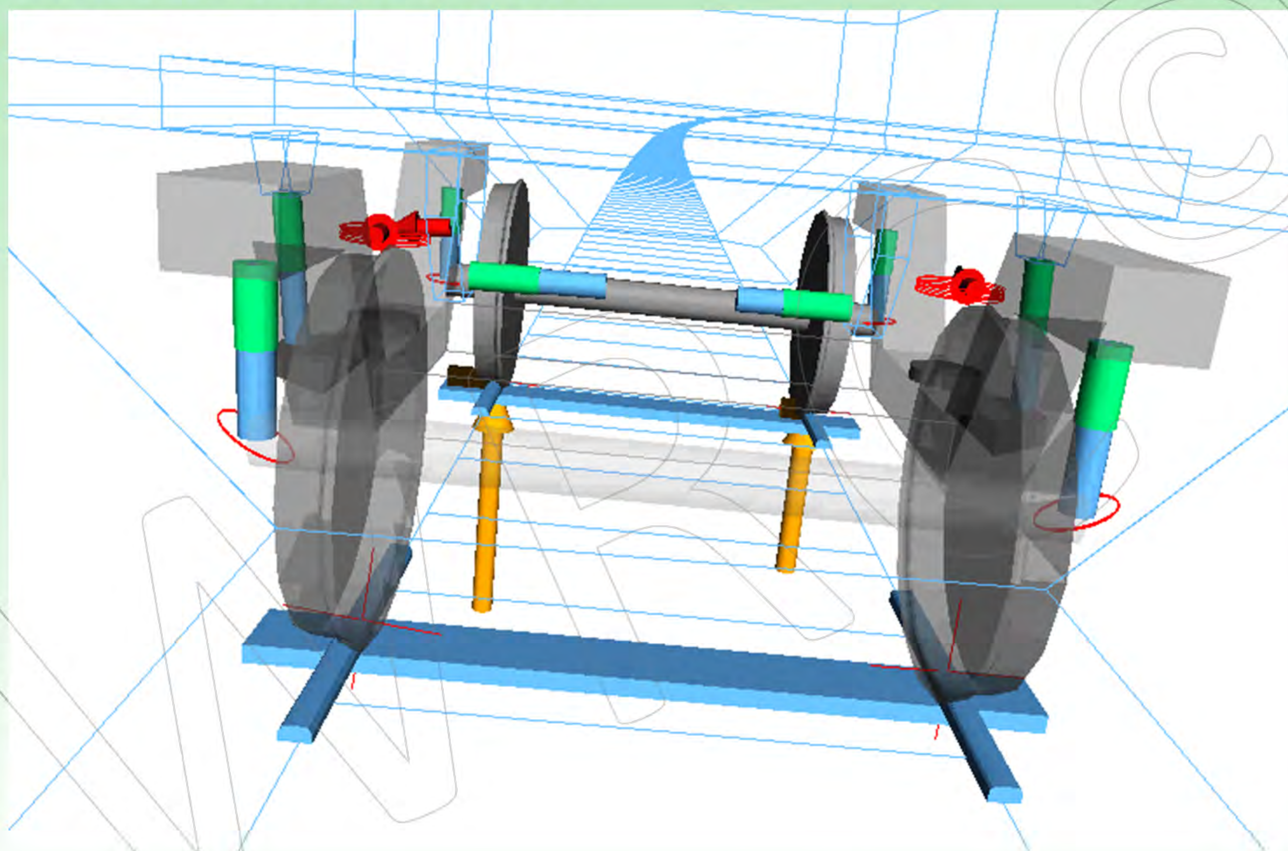
- Integration of Kalker/Vollebregt's CONTACT into SIMPACK
- Postprocessing of SIMPACK results with CONTACT
- Verification of critical simulations with CONTACT
- Easy to handle interface to CONTACT







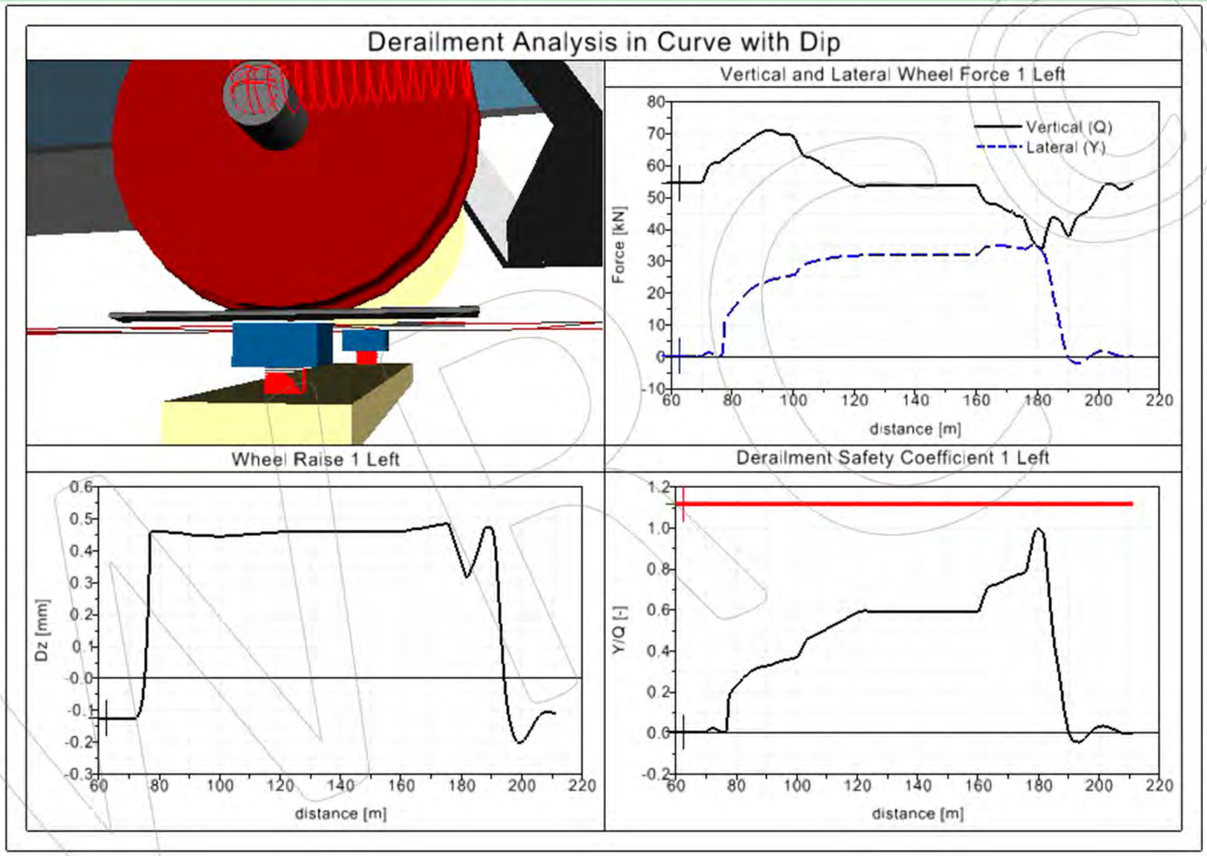
Rail and Wheel Forces



Filters: Low-Pass, Band-Pass,
Sliding Mean/RMS, Percentiles, …

Long Tracks with Irregularities
Q, Y, ΣY, Y/Q, H, ÿ, ÿ⁺, ÿ*, ž, …

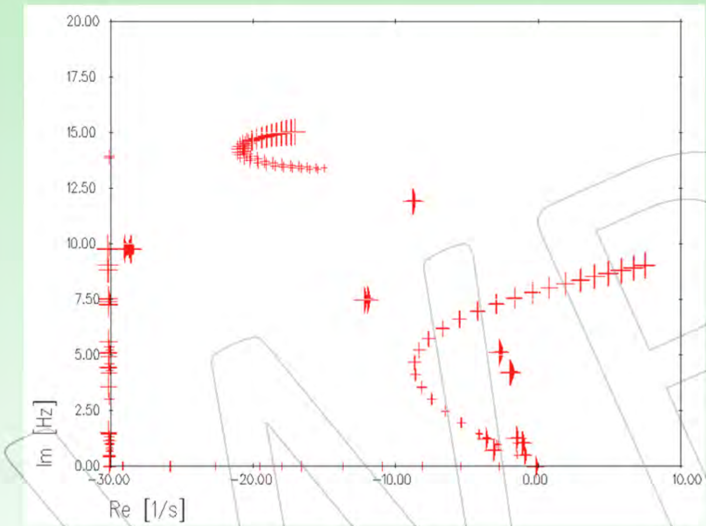
Derailment Safety



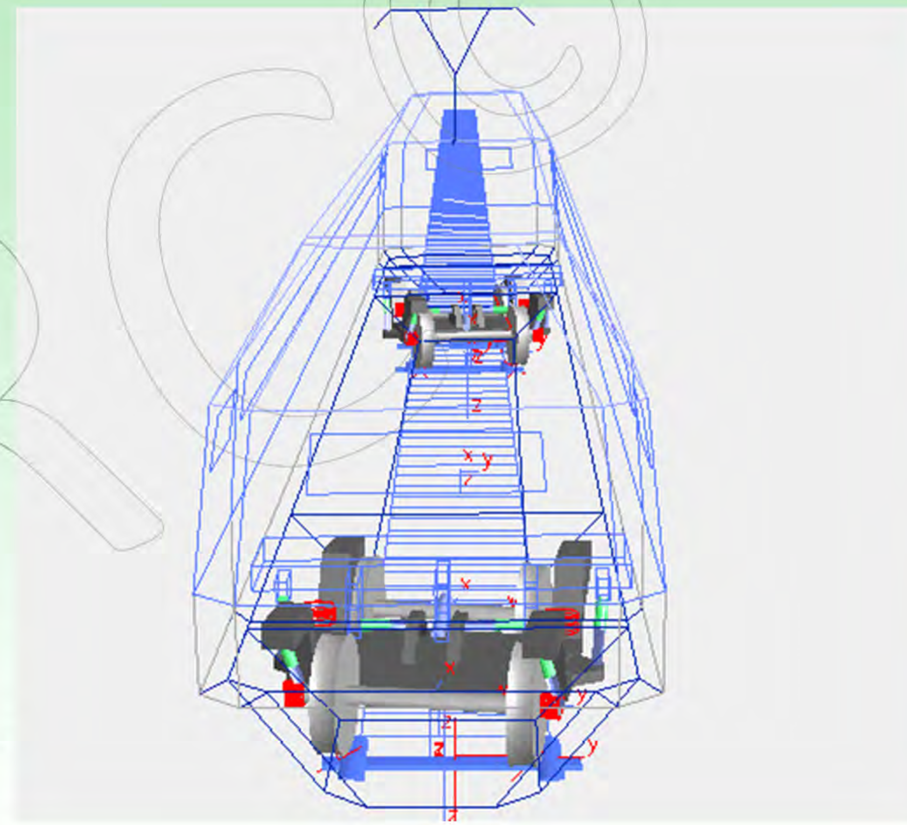
Twisted Track with Dip, Narrow Curves

Q, Y, Y/Q, $\Delta Q/Q_0$, Δz

Running Stability



Non-Linear Time-Domain Analysis
with Track Excitation



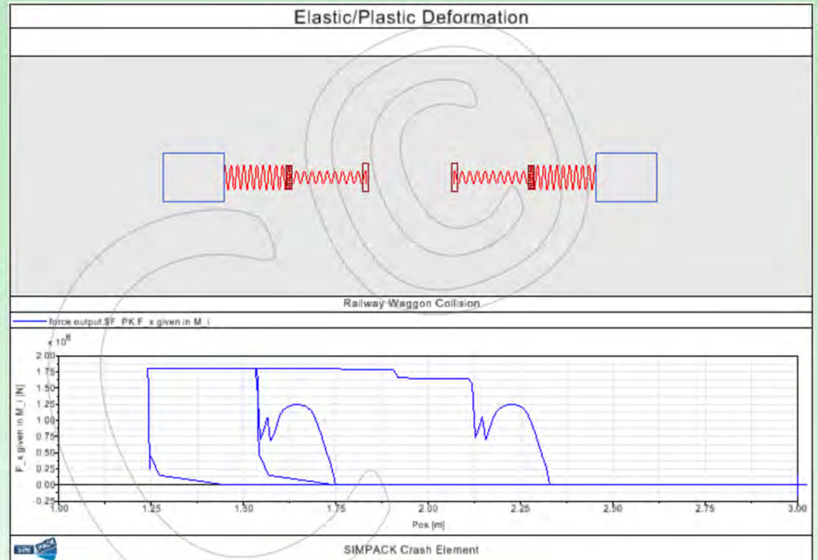
Freight Trains

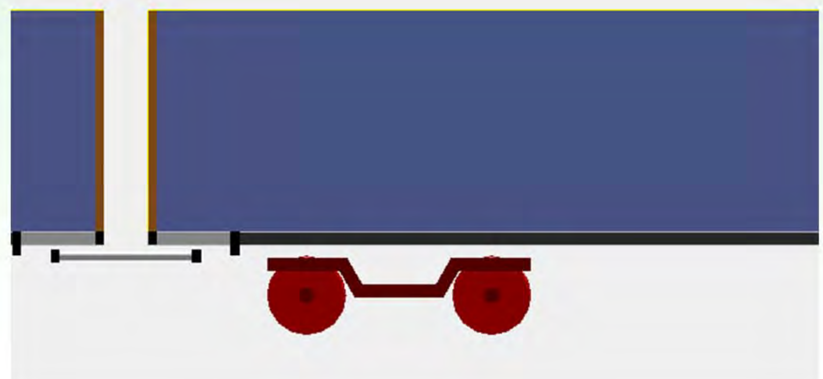
Longitudinal Train and Coupler Dynamics

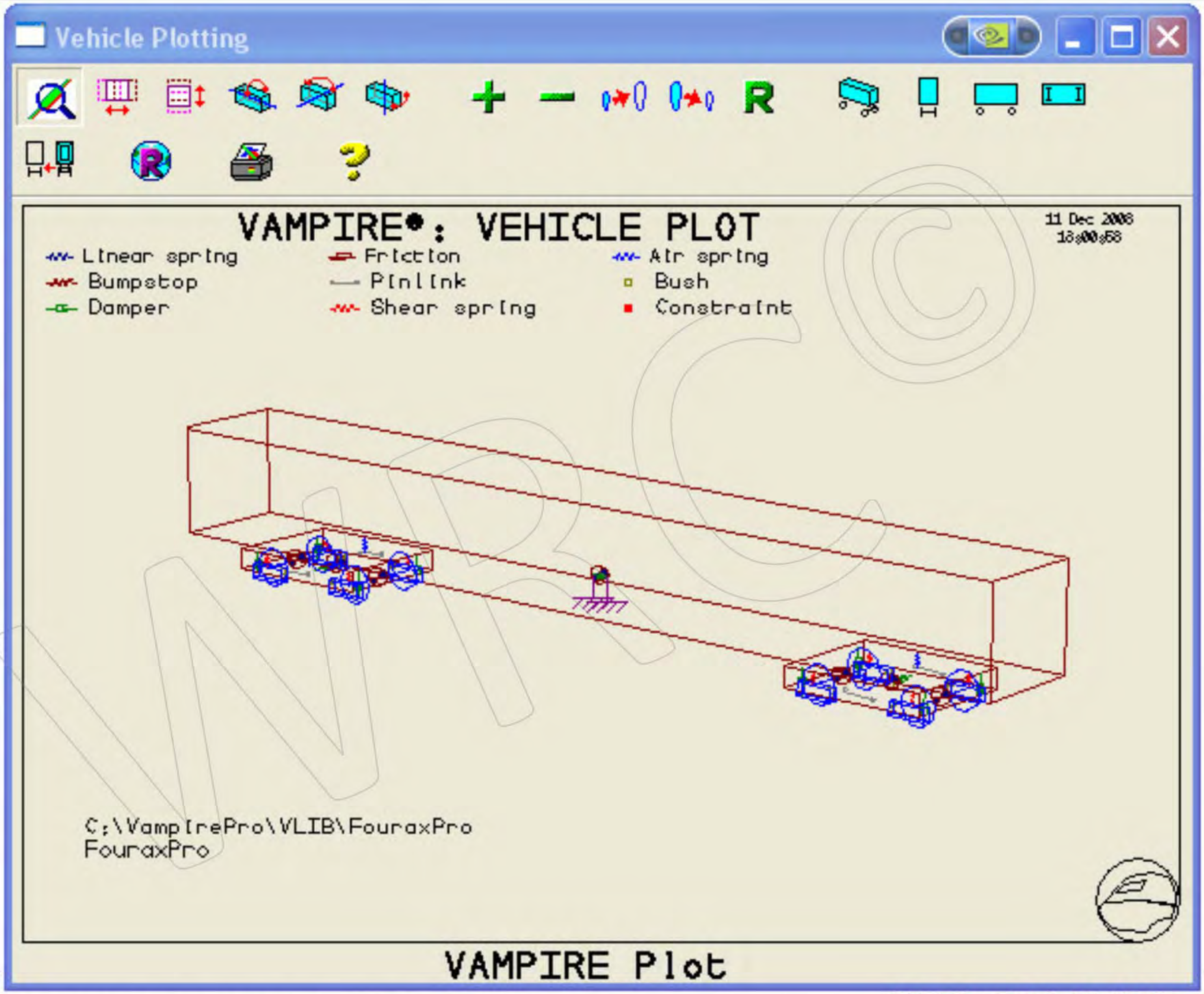
- Buffers
- Cushioned couplers
- Shock absorbers
- Anti-climbing devices

Pneumatic brake system by

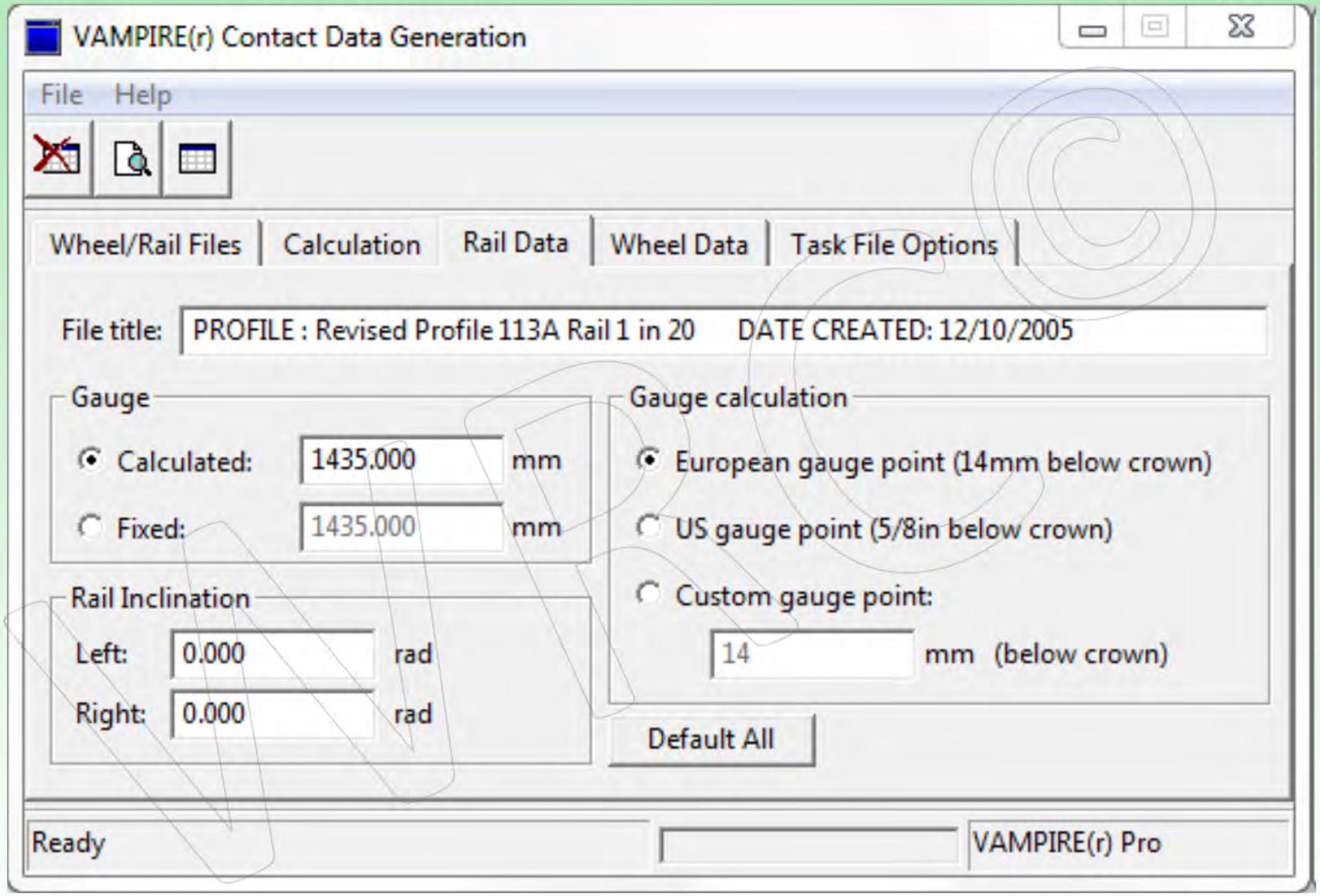
- SIMPACK Control
- External software (SIMPACK FMU Interface)

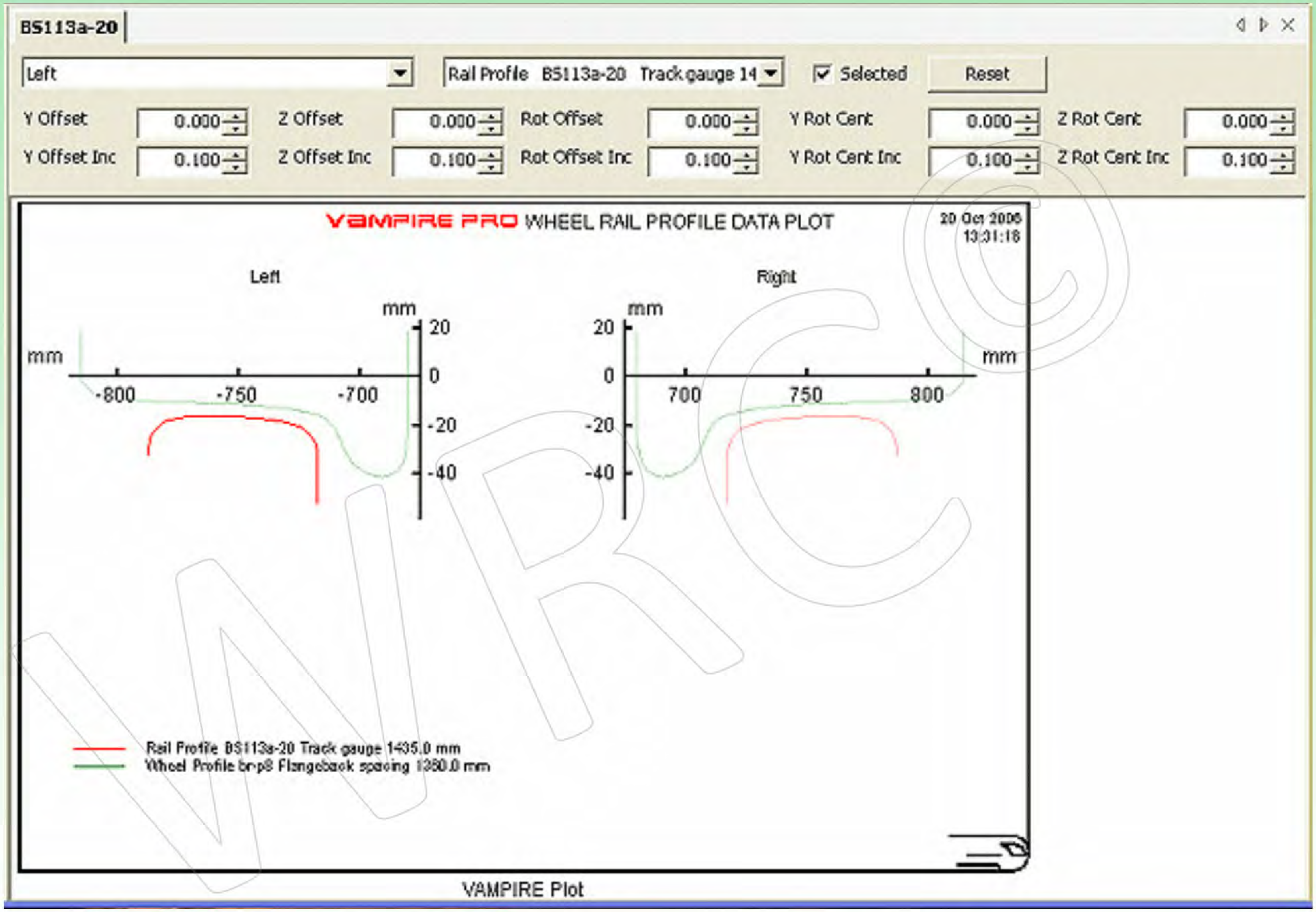






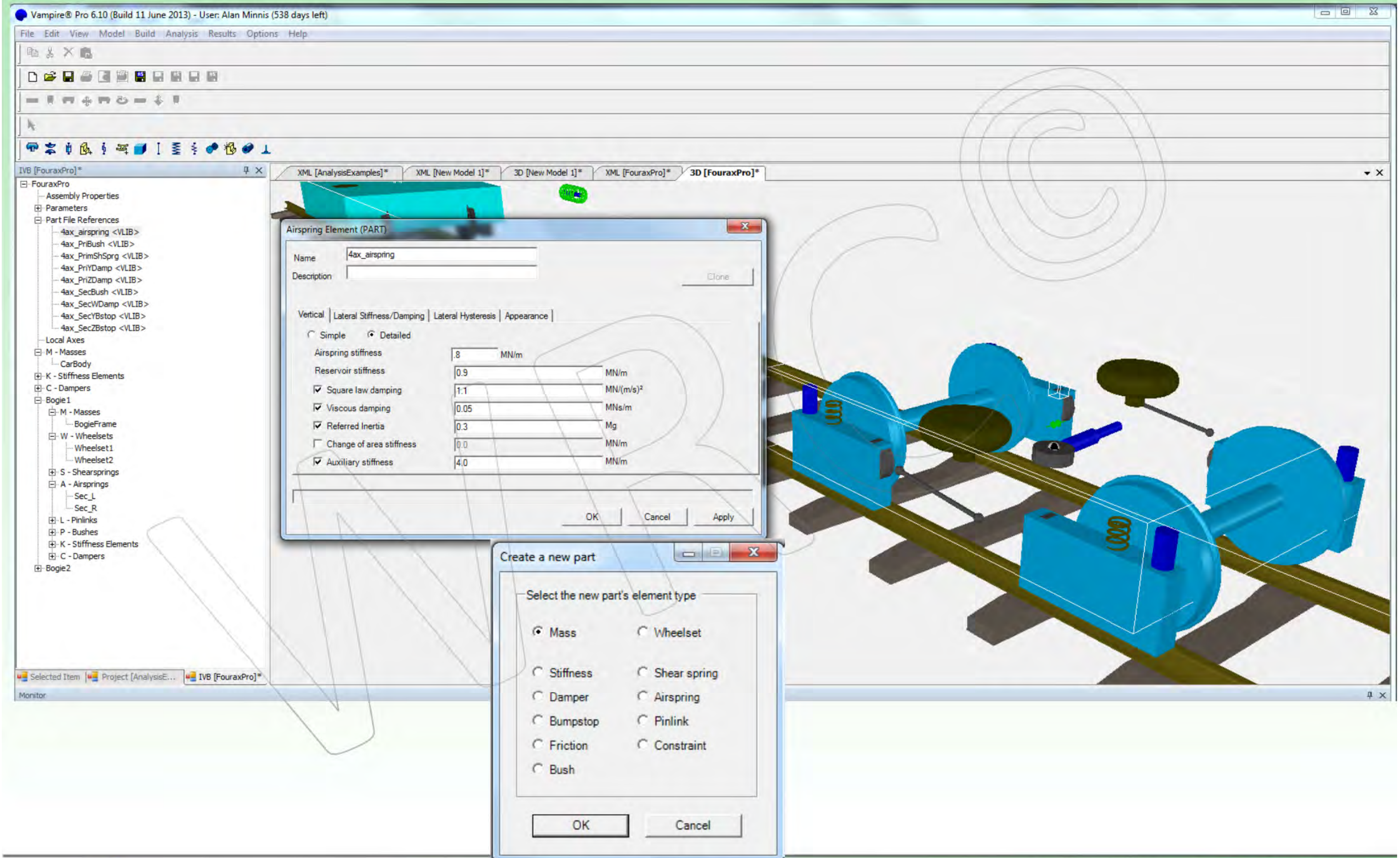
Vehicle Plotting
VAMPIRE®: VEHICLE PLOT
11 Dec 2008
18:00:58
Linear spring
Friction
Air spring
Bumpstop
Pinlink
Bush
Damper
Shear spring
Constraint
C:\VampirePro\VLIB\FouraxPro
FouraxPro
VAMPIRE Plot


VAMPIRE(r) Contact Data Generation
File Help
Wheel/Rail Files
Calculation
Rail Data
Wheel Data
Task File Options
File title: PROFILE : Revised Profile 113A Rail 1 in 20 DATE CREATED: 12/10/2005
Gauge
Calculated: 1435.000 mm
Fixed: 1435.000 mm
Rail Inclination
Left: 0.000 rad
Right: 0.000 rad
Gauge calculation
European gauge point (14mm below crown)
US gauge point (5/8in below crown)
Custom gauge point:
14 mm (below crown)
Default All
Ready
VAMPIRE(r) Pro

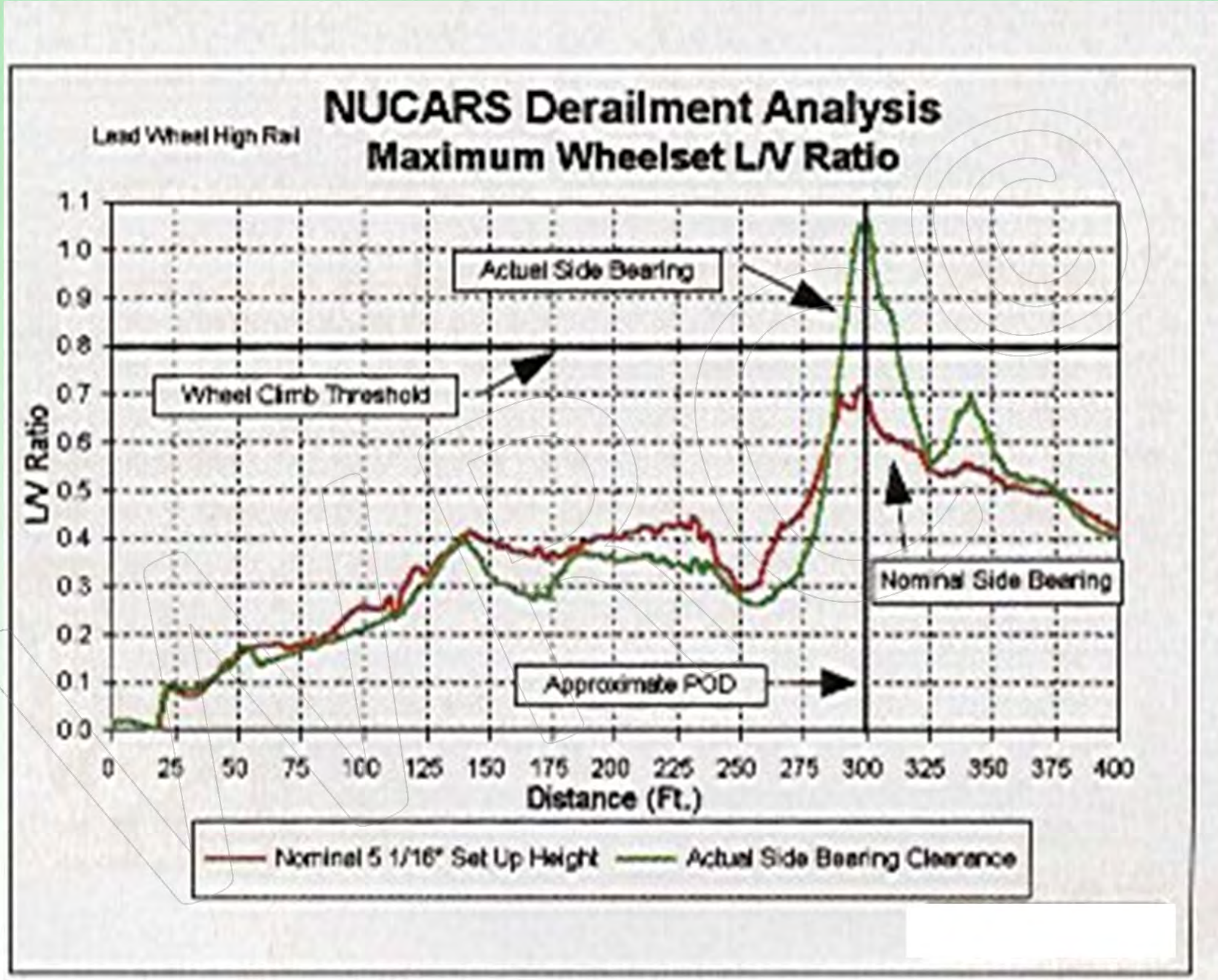


BS113a-20
Left
Rail Profile BS113a-20 Track gauge 14
Selected
Reset
Y Offset 0.000
Z Offset 0.000
Rot Offset 0.000
Y Rot Cent 0.000
Z Rot Cent 0.000
Y Offset Inc 0.100
Z Offset Inc 0.100
Rot Offset Inc 0.100
Y Rot Cent Inc 0.100
Z Rot Cent Inc 0.100
VAMPIRE PRO WHEEL RAIL PROFILE DATA PLOT
20 Oct 2006 13:31:18
Left
Right
mm
20
0
-20
-40
-800
-750
-700
700
750
800
Rail Profile BS113a-20 Track gauge 1435.0 mm
Wheel Profile brp8 Flangeback spacing 1360.0 mm
VAMPIRE Plot

Interactive Vehicle Builder

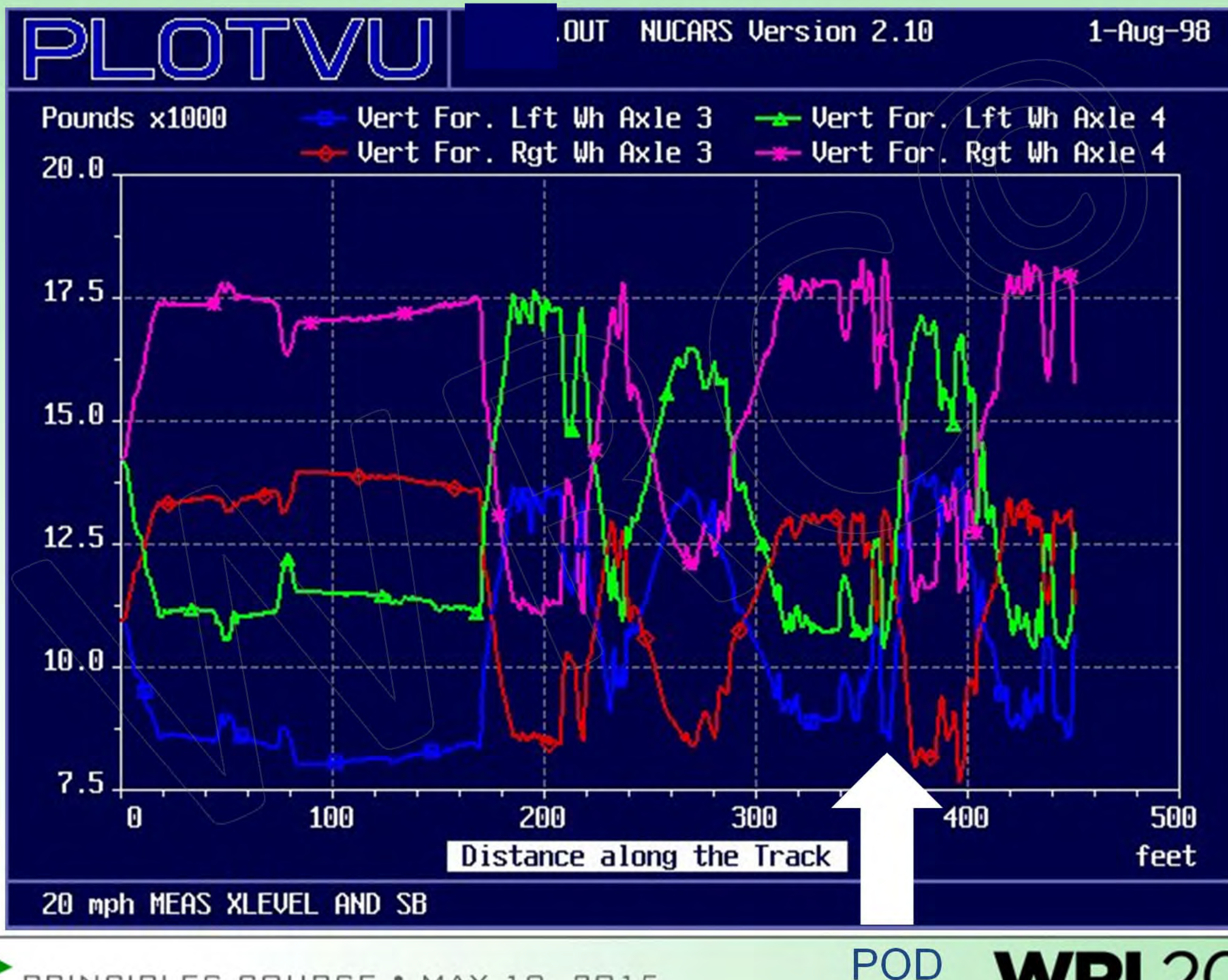


Derailment analysis comparing proper vs. insufficient constant contact side bearing set up height

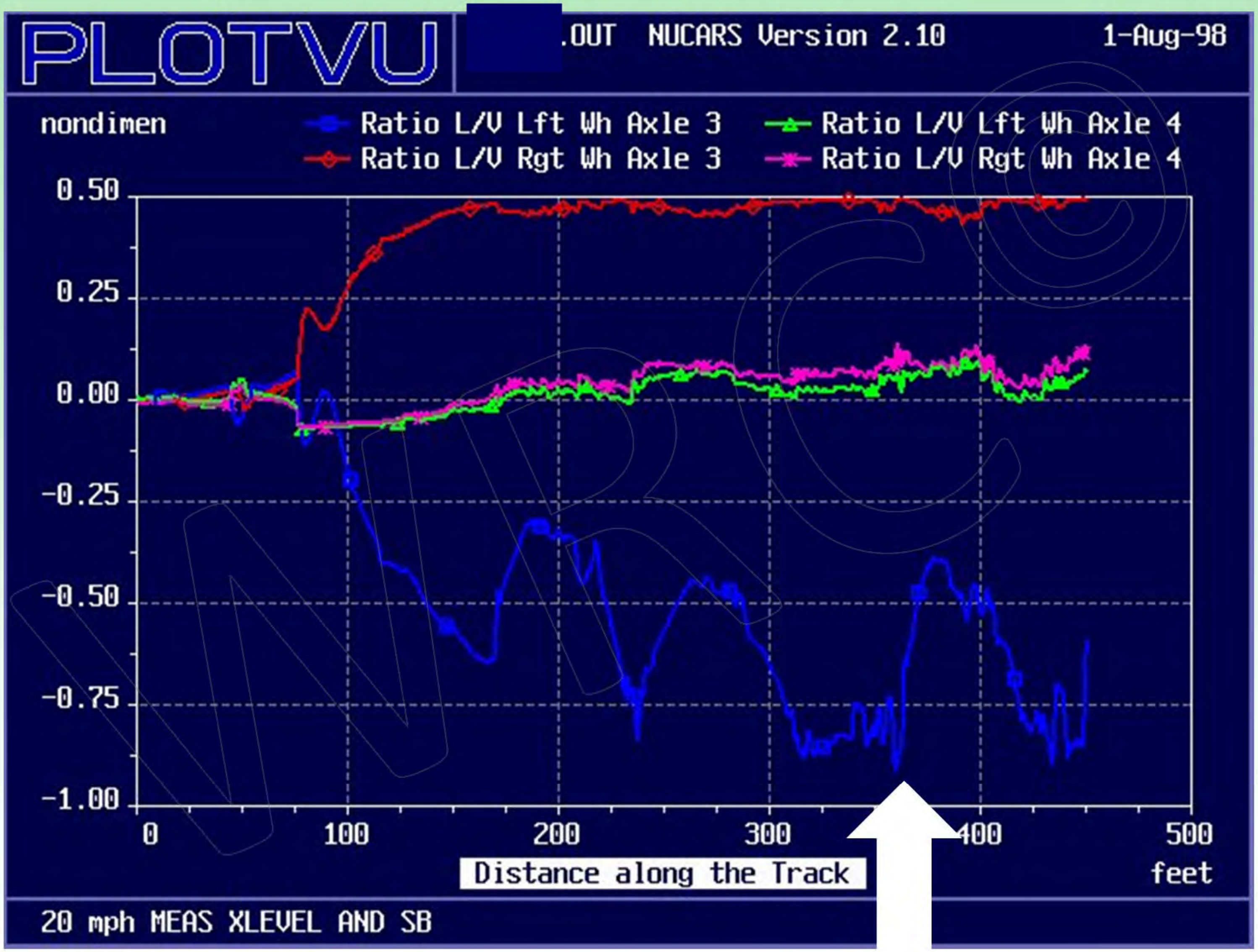

NUCARS Derailment Analysis
Maximum Wheelset L/V Ratio
Lead Wheel High Rail
Actual Side Bearing
Wheel Climb Threshold
Nominal Side Bearing
Approximate POD
L/V Ratio
Distance (Ft.)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
Nominal 5 1/16" Set Up Height
Actual Side Bearing Clearance

Derailment analysis investigating effect of track twist

Wheel unloading due to crosslevel twist



Wheel unloading due to crosslevel twist



POD

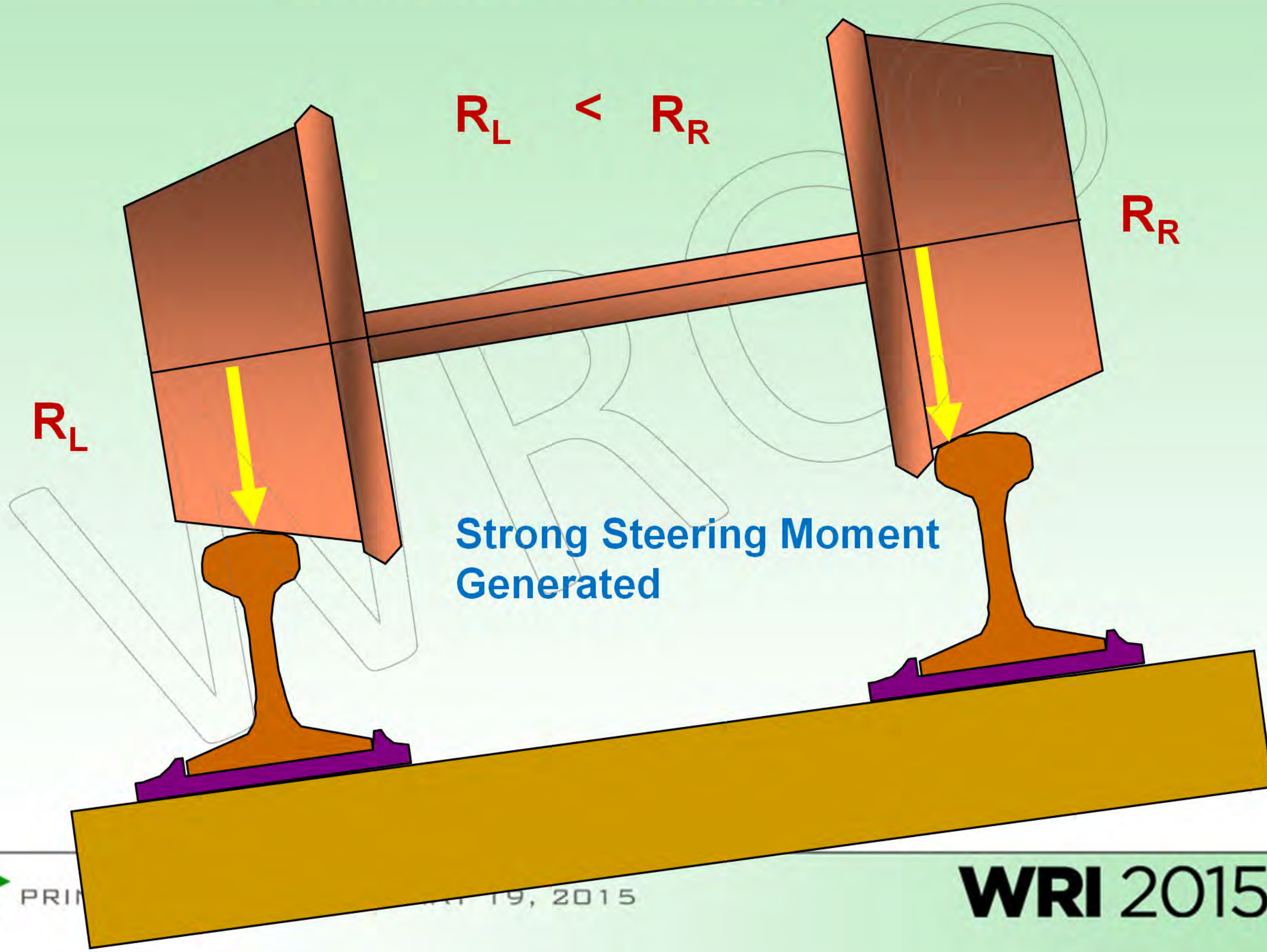
Longitudinal Steering Moment

- The goal of wheelset steering is to develop a larger radius on High Rail vs. Low Rail

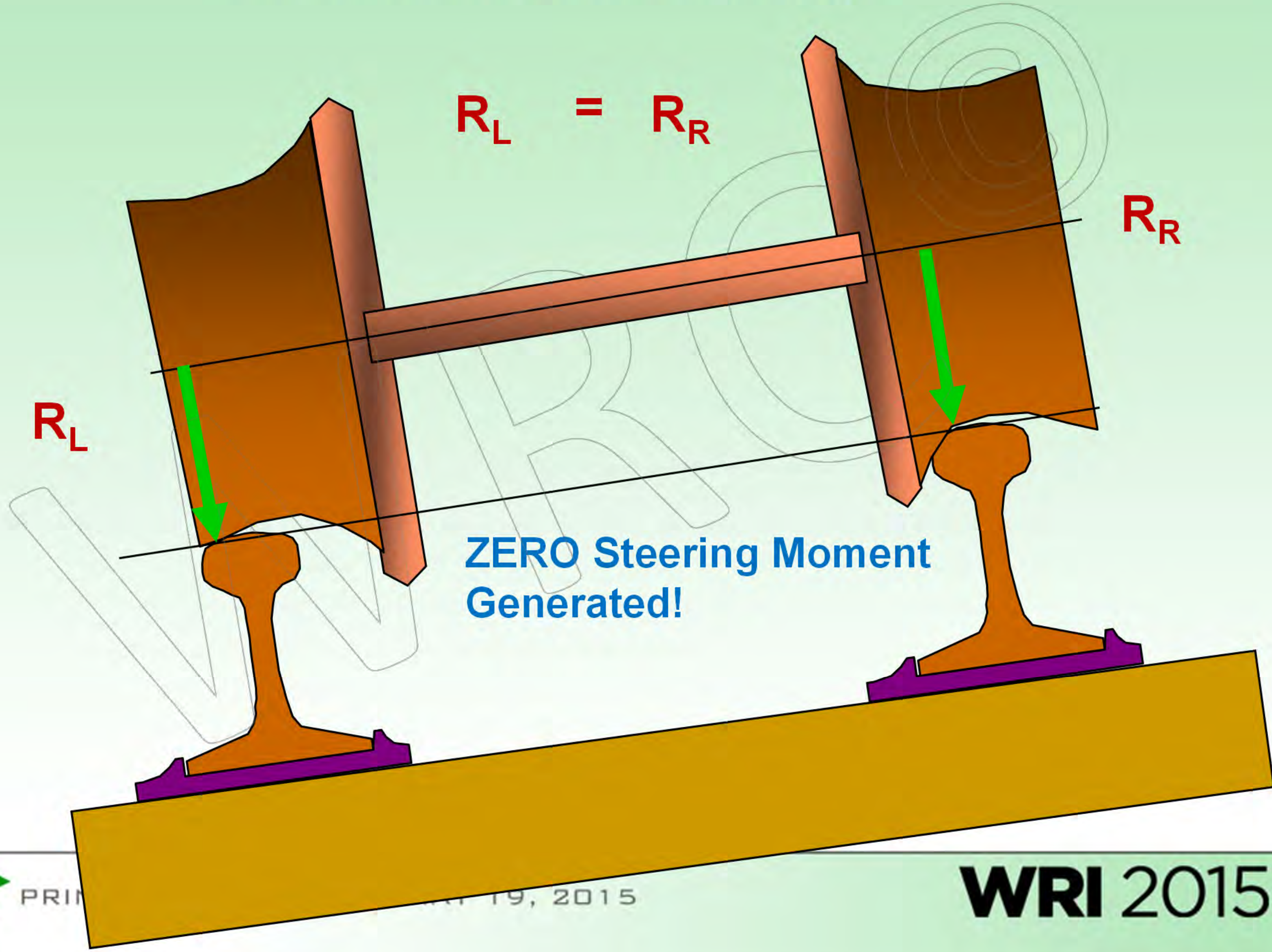
What Factors Reduce Steering Moment

- Hollow Worn Wheels, False Flanges
- Over-lubrication of High Rail
- Severe Two-Point Wheel-Rail Contact
- Wheel Tape Mismatches

Normal Curving



Hollow Wheel Curving



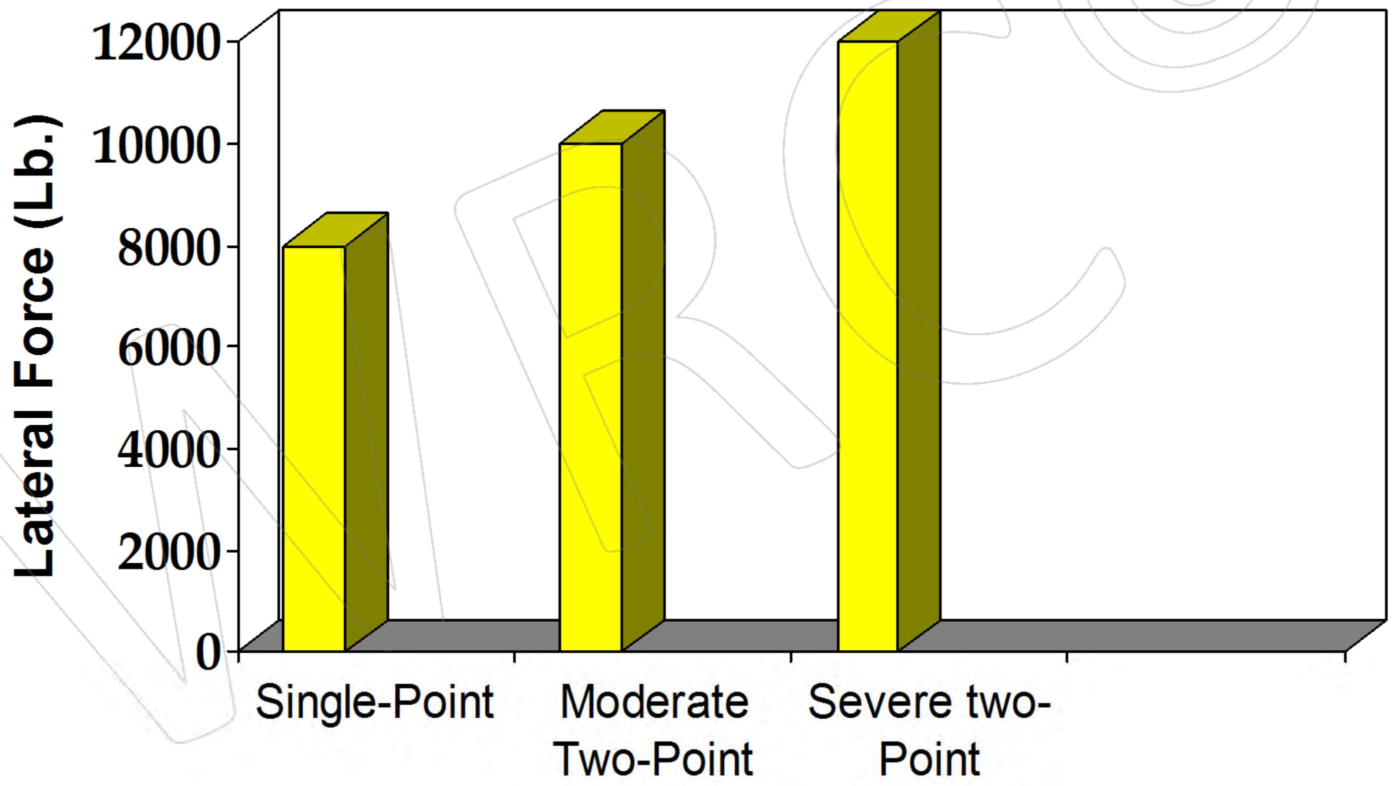
Wheel/Rail Contact Geometry

Single Point Contact

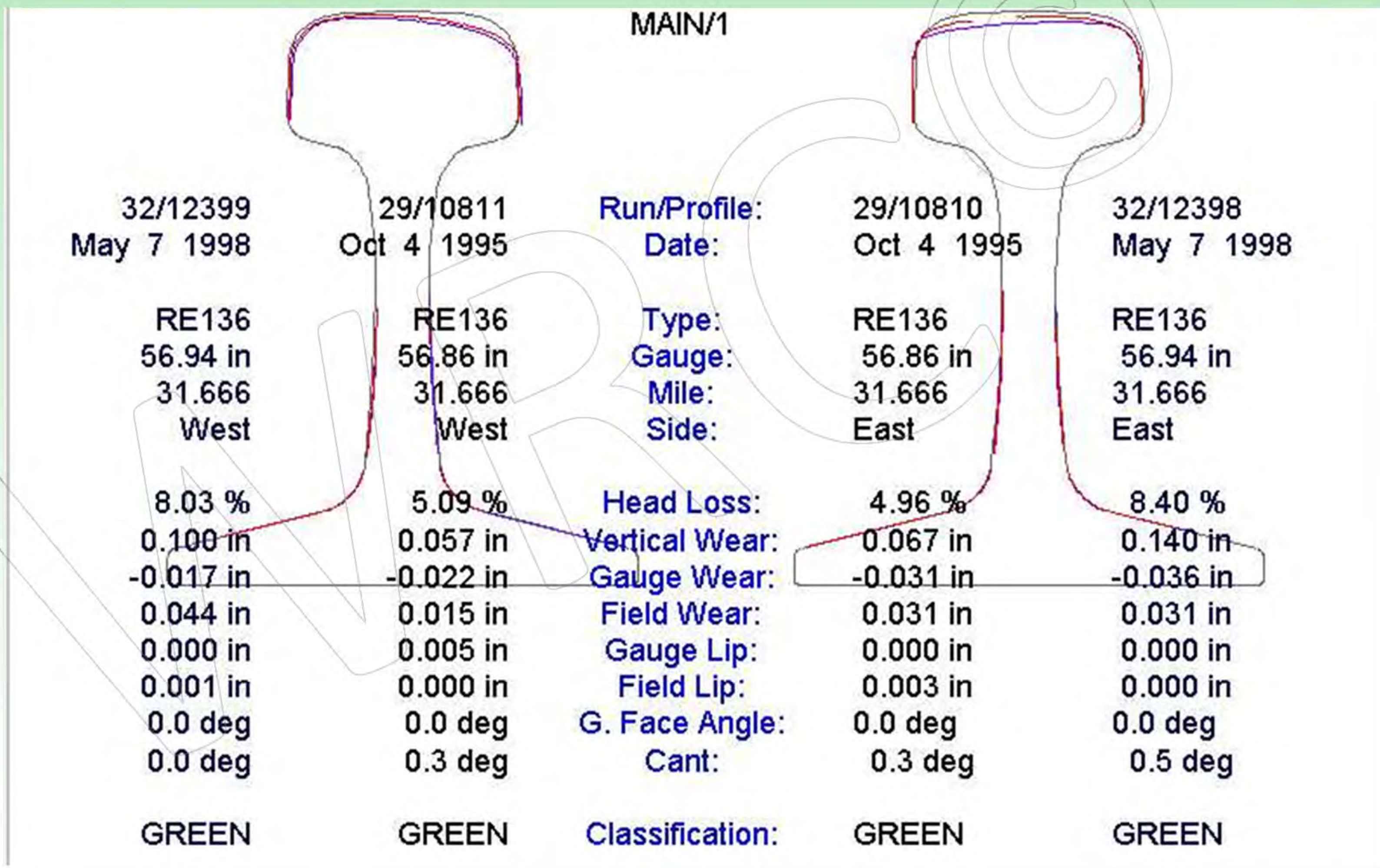
Moderate two-point Contact

Severe two-point Contact

Average Low Rail Lateral Forces for Different Rail Profiles

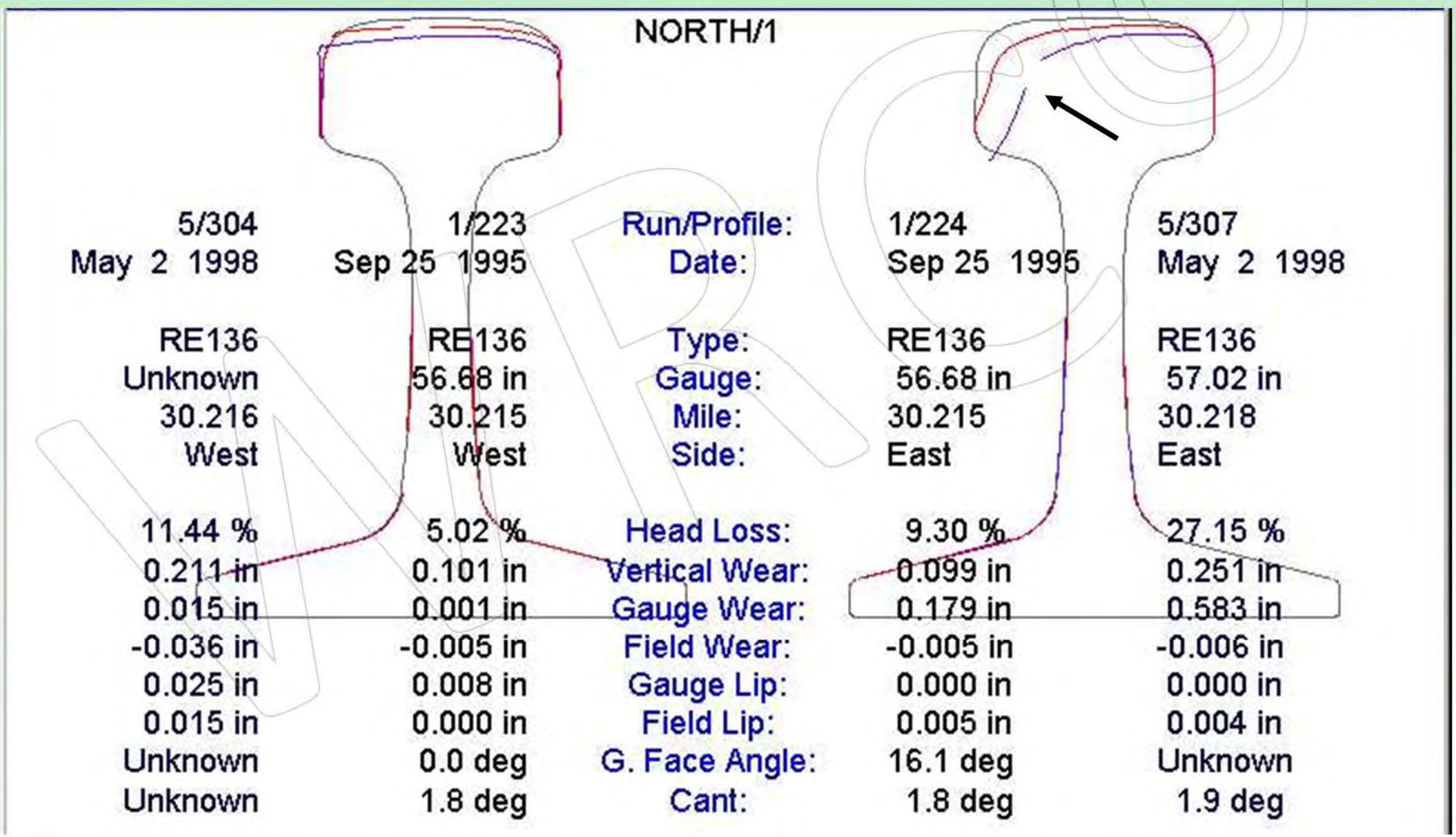


Subdivision 1 - Proper Rail Profile



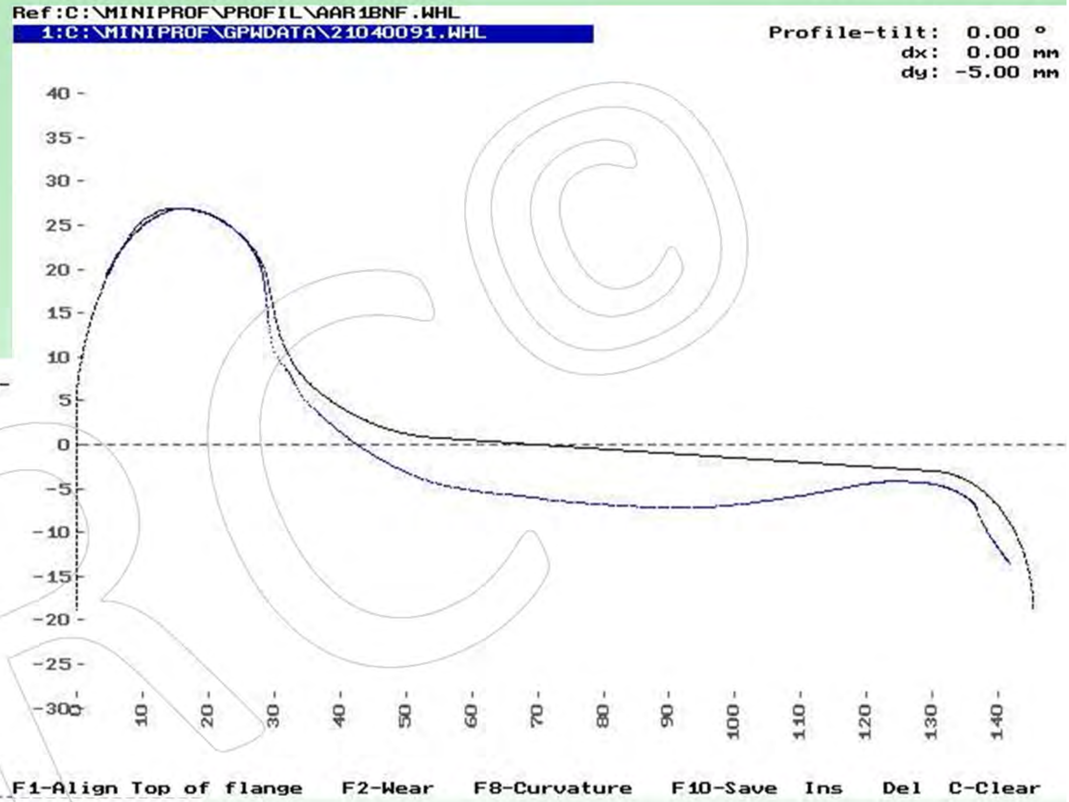
32/12399	29/10811	Run/Profile:	29/10810	32/12398
May 7 1998	Oct 4 1995	Date:	Oct 4 1995	May 7 1998
RE136	RE136	Type:	RE136	RE136
56.94 in	56.86 in	Gauge:	56.86 in	56.94 in
31.666	31.666	Mile:	31.666	31.666
West	West	Side:	East	East
8.03 %	5.09 %	Head Loss:	4.96 %	8.40 %
0.100 in	0.057 in	Vertical Wear:	0.067 in	0.140 in
-0.017 in	-0.022 in	Gauge Wear:	-0.031 in	-0.036 in
0.044 in	0.015 in	Field Wear:	0.031 in	0.031 in
0.000 in	0.005 in	Gauge Lip:	0.000 in	0.000 in
0.001 in	0.000 in	Field Lip:	0.003 in	0.000 in
0.0 deg	0.0 deg	G. Face Angle:	0.0 deg	0.0 deg
0.0 deg	0.3 deg	Cant:	0.3 deg	0.5 deg
GREEN	GREEN	Classification:	GREEN	GREEN

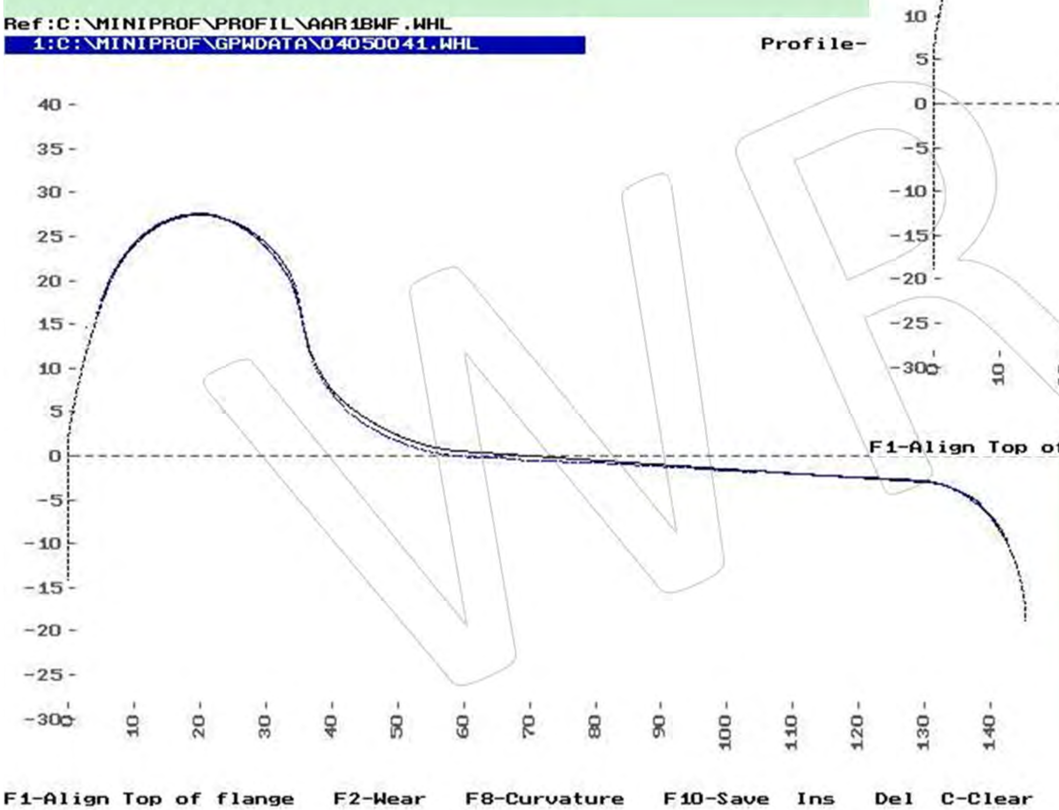
Subdivision 2 - Heavy Gage Corner Wear High Rail, Minimal Field Side Relief Low Rail



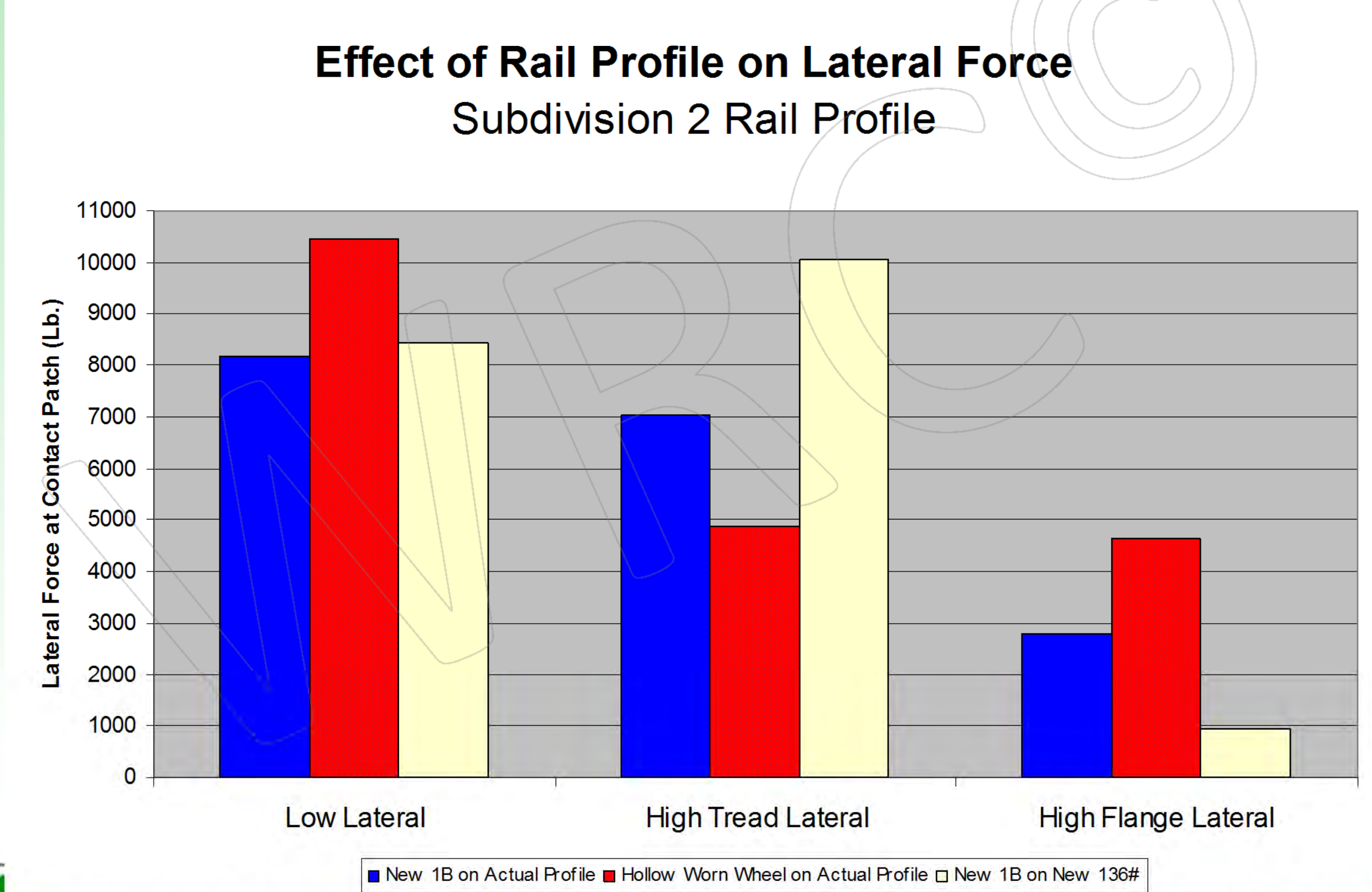
5/304	1/223	Run/Profile:	1/224	5/307
May 2 1998	Sep 25 1995	Date:	Sep 25 1995	May 2 1998
RE136	RE136	Type:	RE136	RE136
Unknown	56.68 in	Gauge:	56.68 in	57.02 in
30.216	30.215	Mile:	30.215	30.218
West	West	Side:	East	East
11.44 %	5.02 %	Head Loss:	9.30 %	27.15 %
0.211 in	0.101 in	Vertical Wear:	0.099 in	0.251 in
0.015 in	0.001 in	Gauge Wear:	0.179 in	0.583 in
-0.036 in	-0.005 in	Field Wear:	-0.005 in	-0.006 in
0.025 in	0.008 in	Gauge Lip:	0.000 in	0.000 in
0.015 in	0.000 in	Field Lip:	0.005 in	0.004 in
Unknown	0.0 deg	G. Face Angle:	16.1 deg	Unknown
Unknown	1.8 deg	Cant:	1.8 deg	1.9 deg

Wheel Profiles



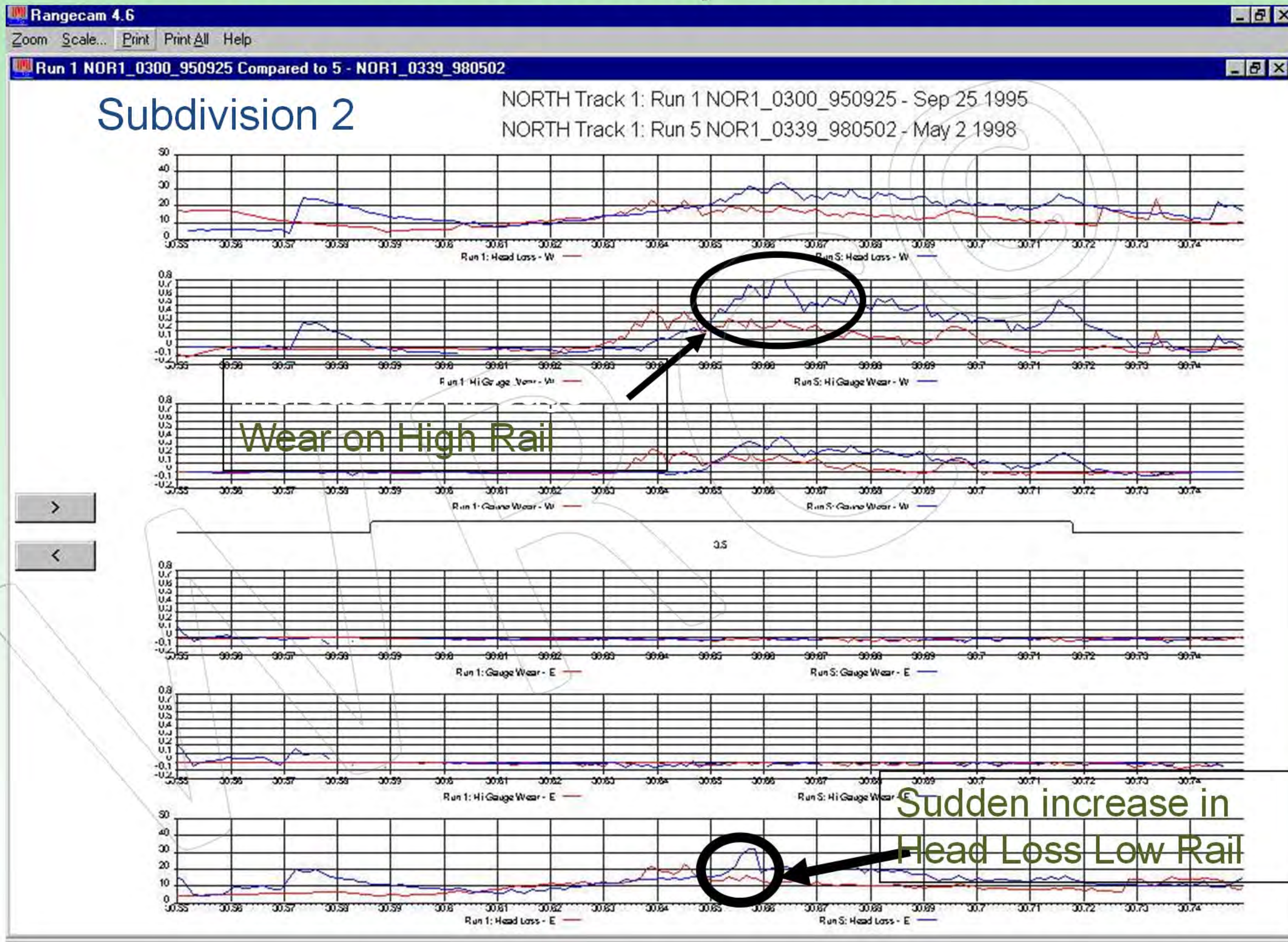


New AAR 1B and Hollow Worn Wheel on Sub 2 Rail Profile and New Rail

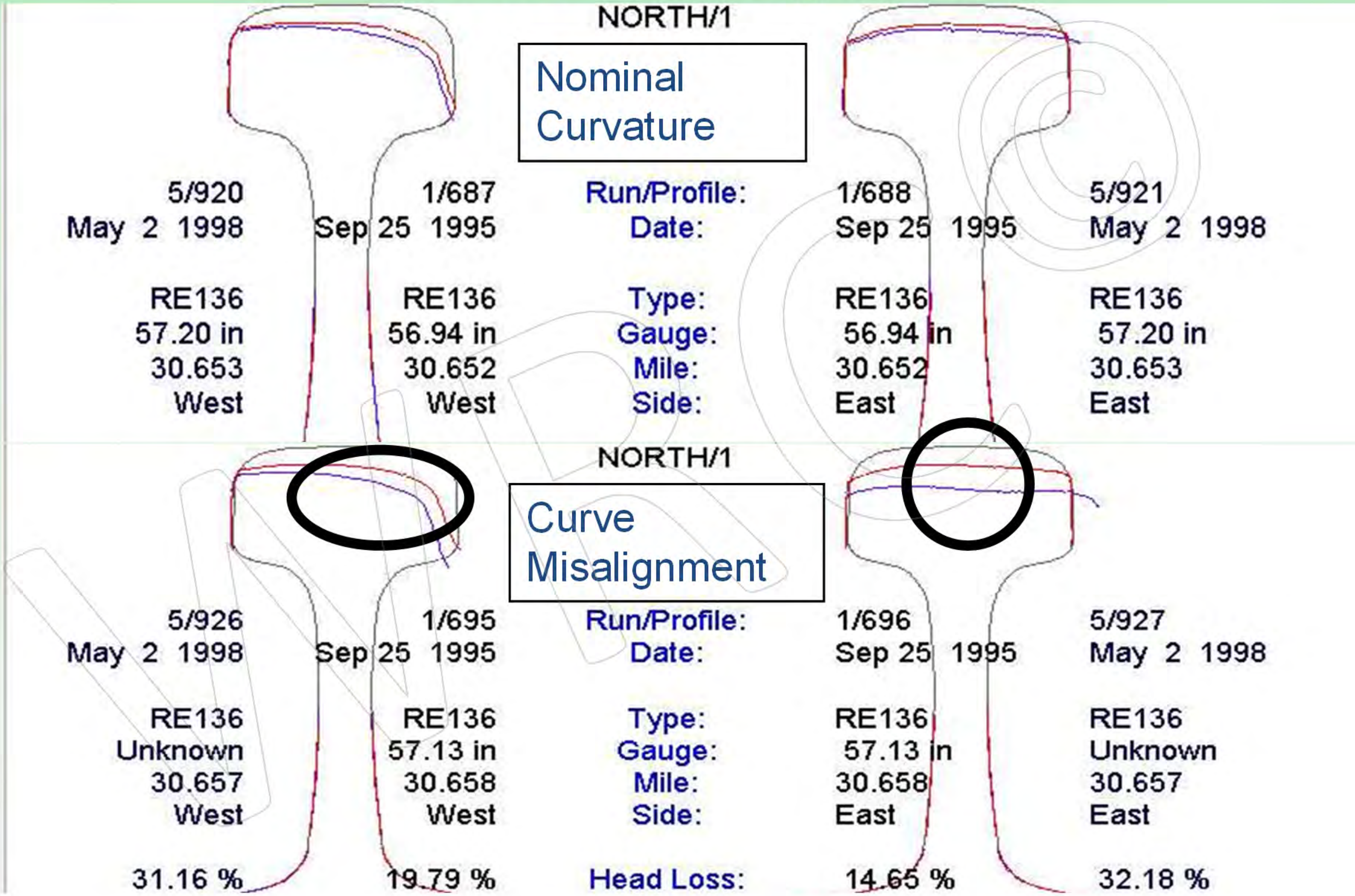


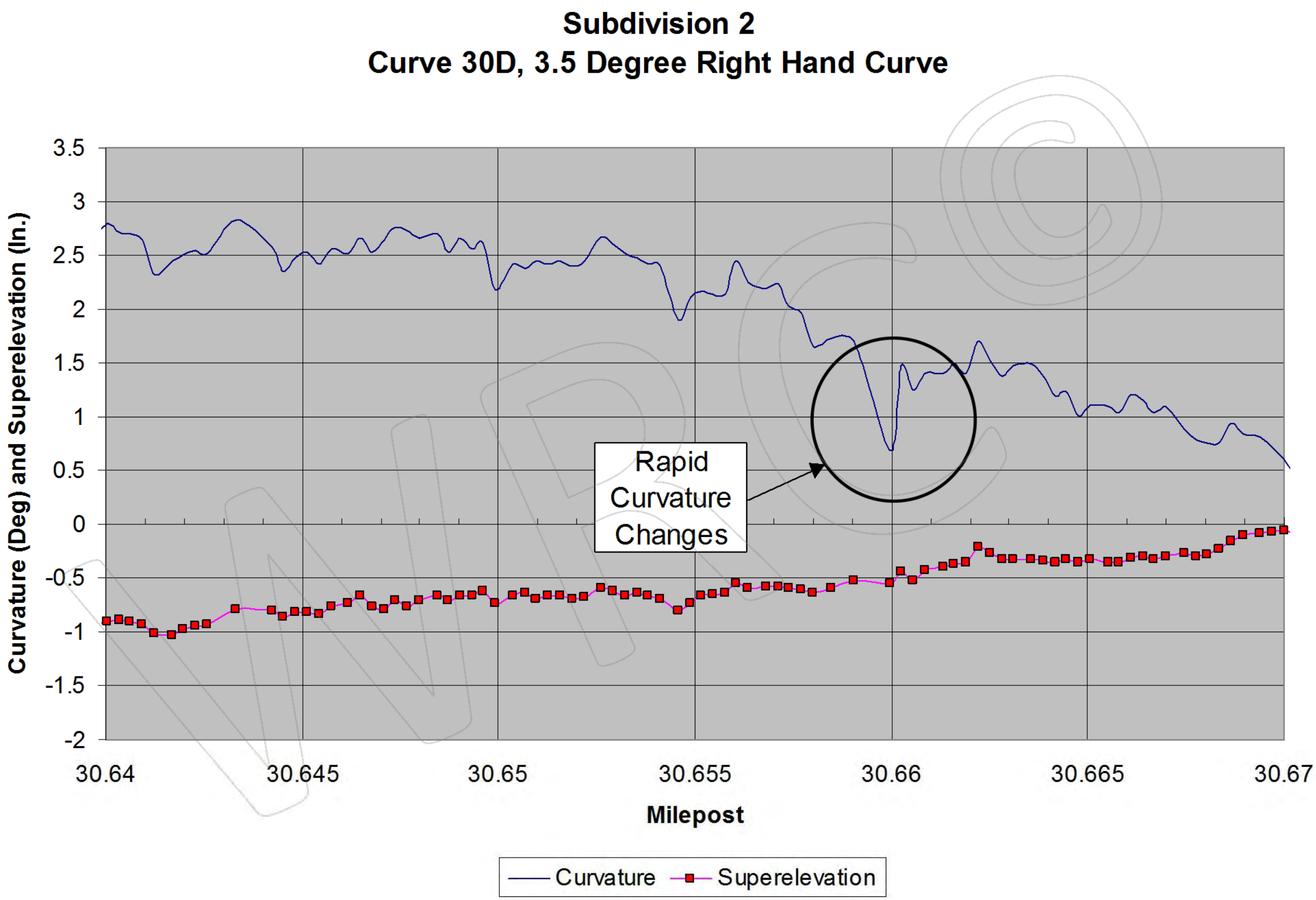
Effect of track geometry (curve misalignment) on rail wear in a curve

Effect of Track Geometry on Rail Wear

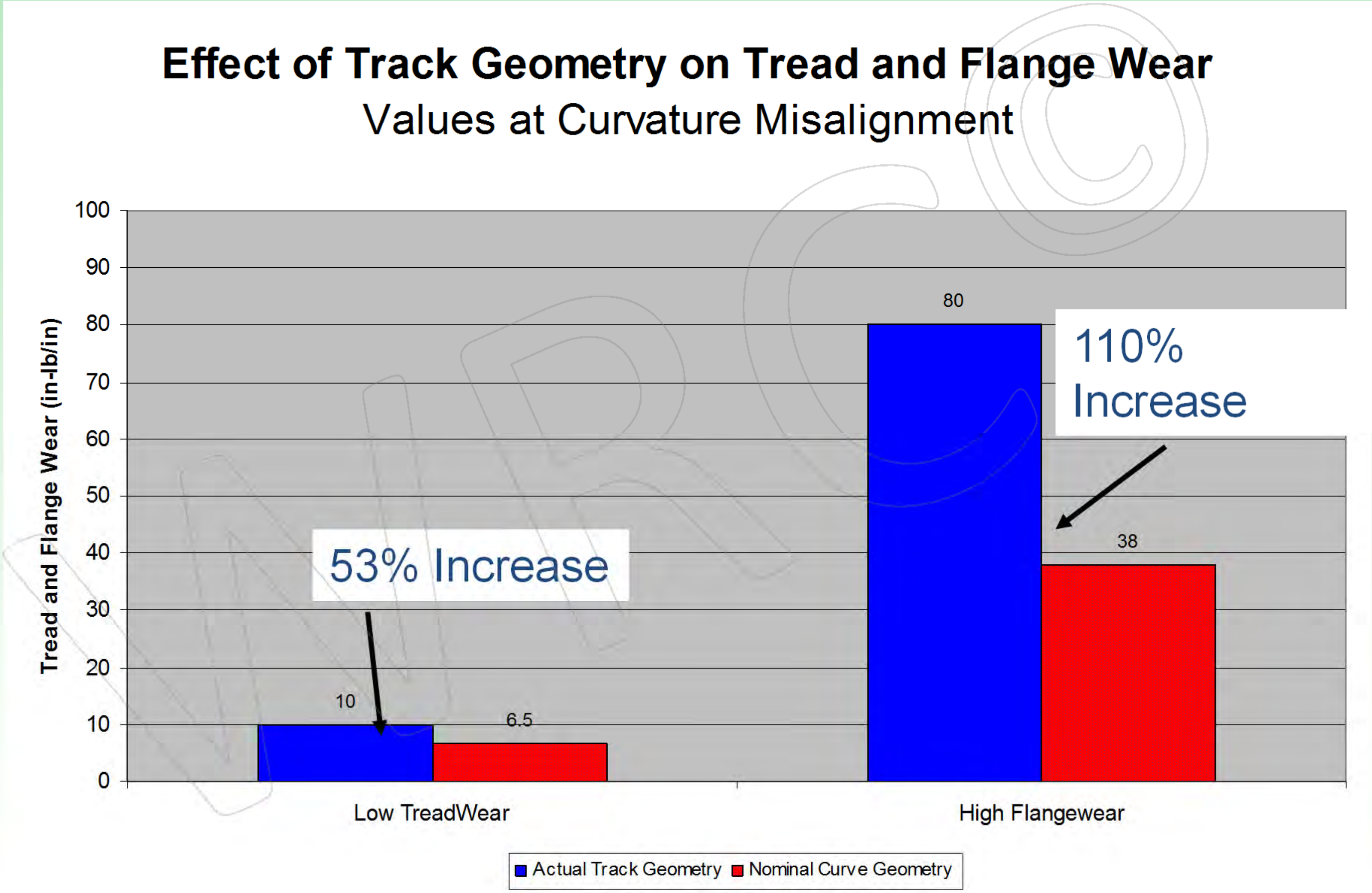


Rail Profiles At Nominal Curvature and at Curve Misalignment




Subdivision 2
Curve 30D, 3.5 Degree Right Hand Curve
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Curvature (Deg) and Superelevation (In.)
Rapid Curvature Changes
30.64
30.645
30.65
30.655
30.66
30.665
30.67
Milepost
Curvature
Superelevation

Effect of Curvature Anomaly on Tread and Flange Wear



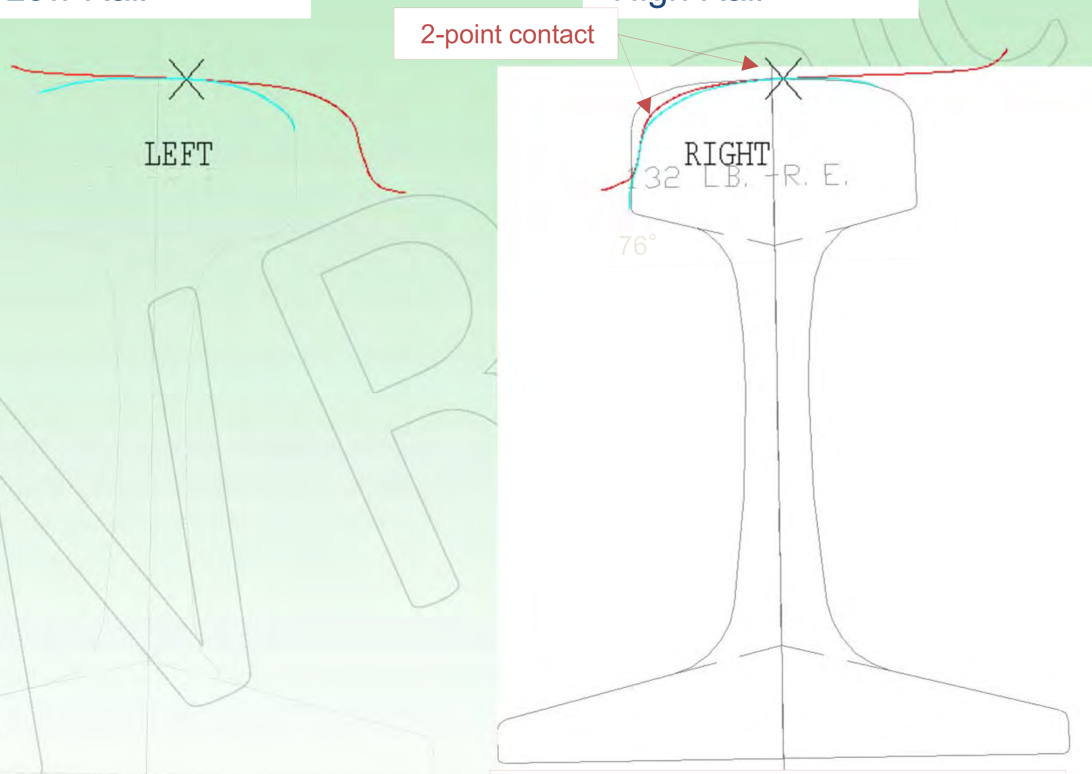
Case 1. Derailment in Curve of Doublestack Car with Hollow Worn Wheel

Wheel-Rail Contact Geometry

Lead Axle - DTTX 54214

Low Rail

High Rail



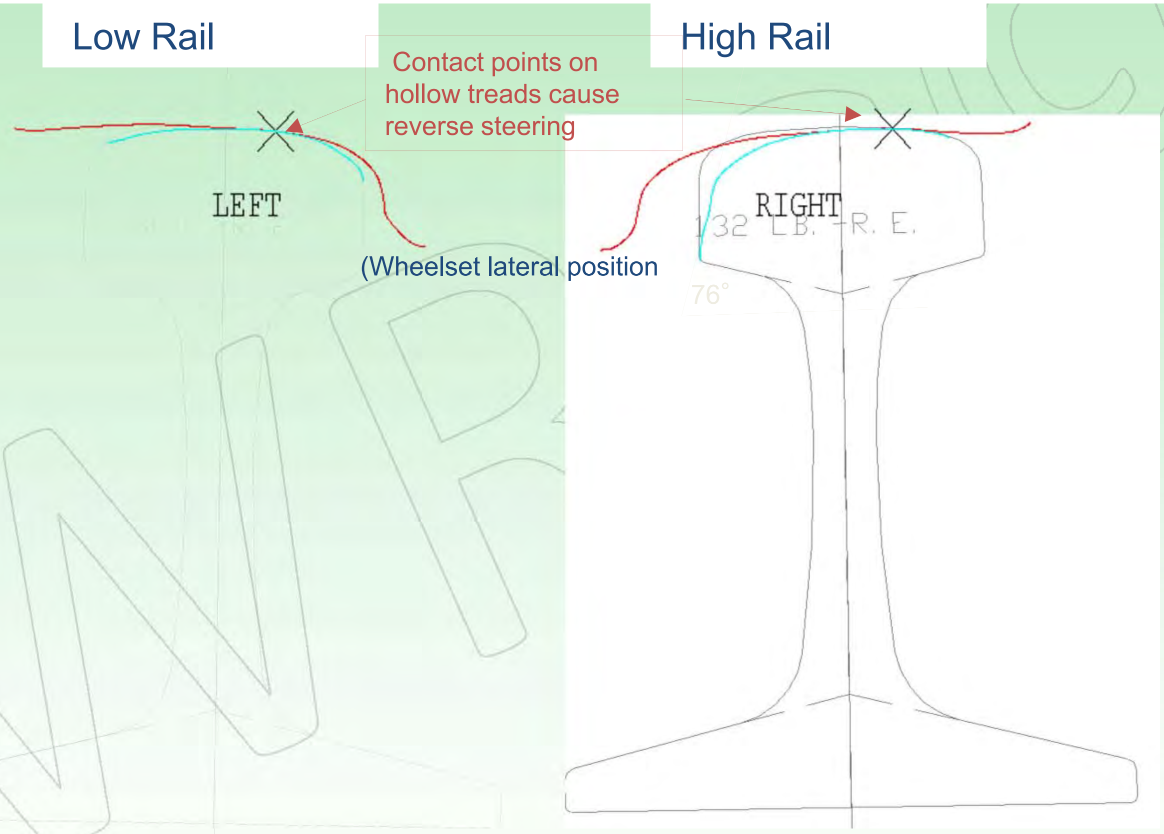
2-point contact, loss of steering

Gage face angle 76°

Flange climb more likely

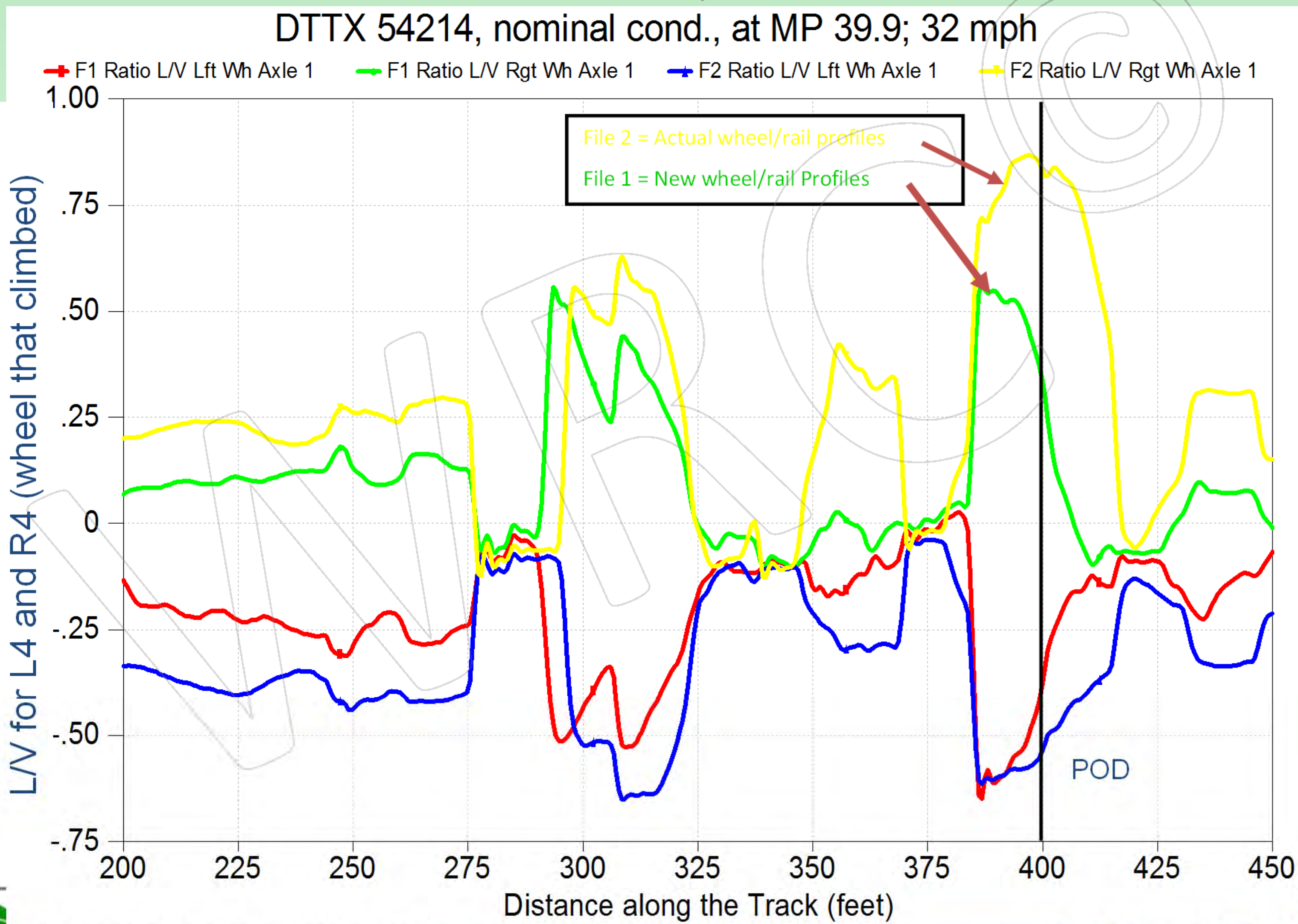
Wheel-Rail Contact Geometry

Second Axle - DTTX 54214



Simulation Results

Effect of Wheel/Rail Profiles



Case 2.
Derailment of Locomotive with Asymmetrical Wheel Wear on switch point rail

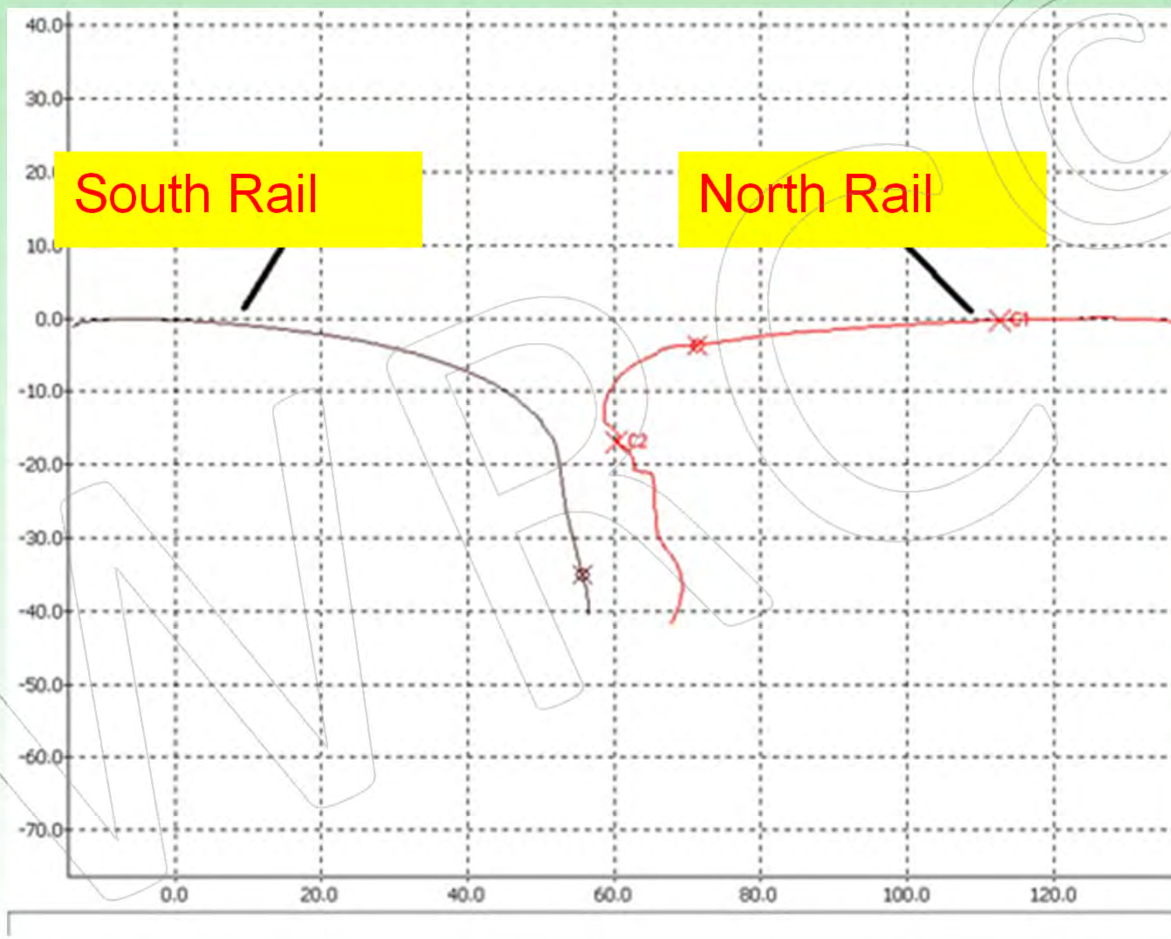
Background

- The train was operating at 28 mph in dynamic brake #3 at the time of the derailment.
- Locomotive was SD90MAC equipped with HTCR (radial steering) trucks.
- The wheels of the #4 axle revealed asymmetric flange wear. L4 is 3 tape sizes smaller (~3mm, 0.118-in) than R4. The L4 flange wear is greater than the R4.
- L4 does not "take the gauge" for thin flange.
- Track observations showed joints in both running rails with vertical deflection (pumping) 5-ft ahead of the POD at the points.
- Gauge face wear and head-crushing were also evident in the 5-ft. ahead of the switch.
- The L4 wheel of Locomotive, climbed the point end of the point rail of a crossover switch. The switch was lined for the diverging route from Main #2 to Main #1.

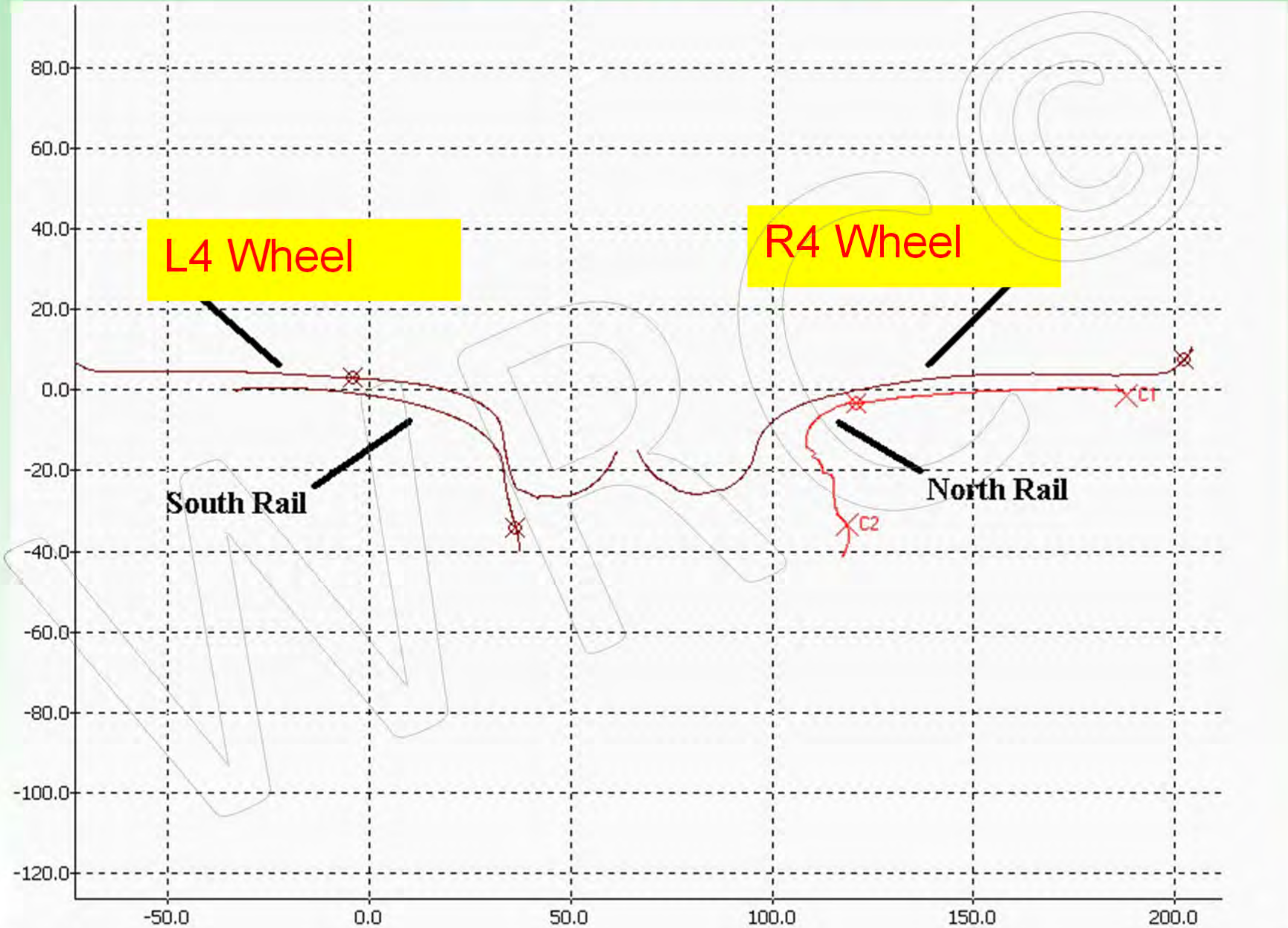
Wheel Profiles

These profiles confirm that Axle 4 has been "crowding" consistently toward the Left side, causing asymmetric wear to the wheel flanges

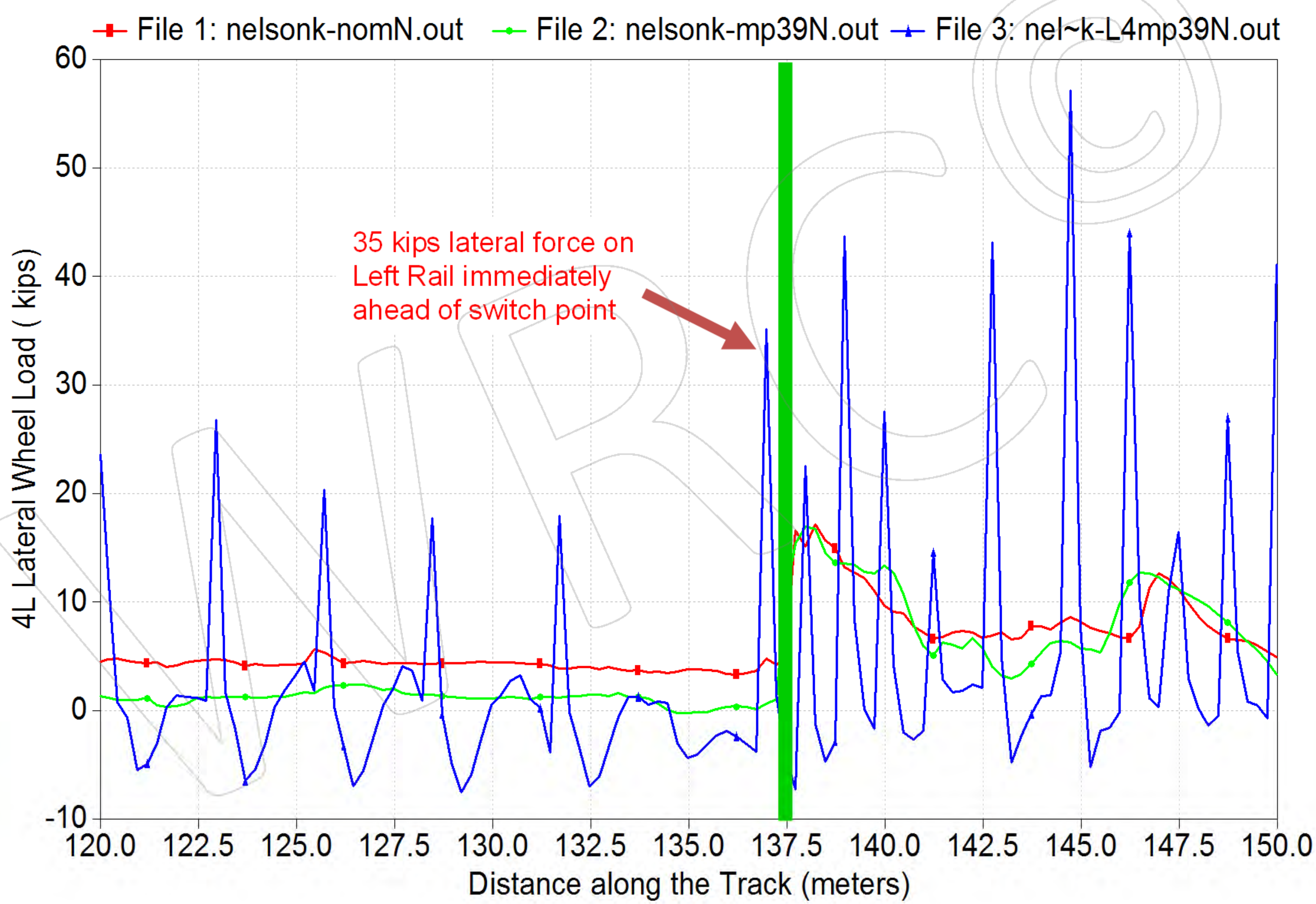
Rail Sections



Wheel and Rail Profiles

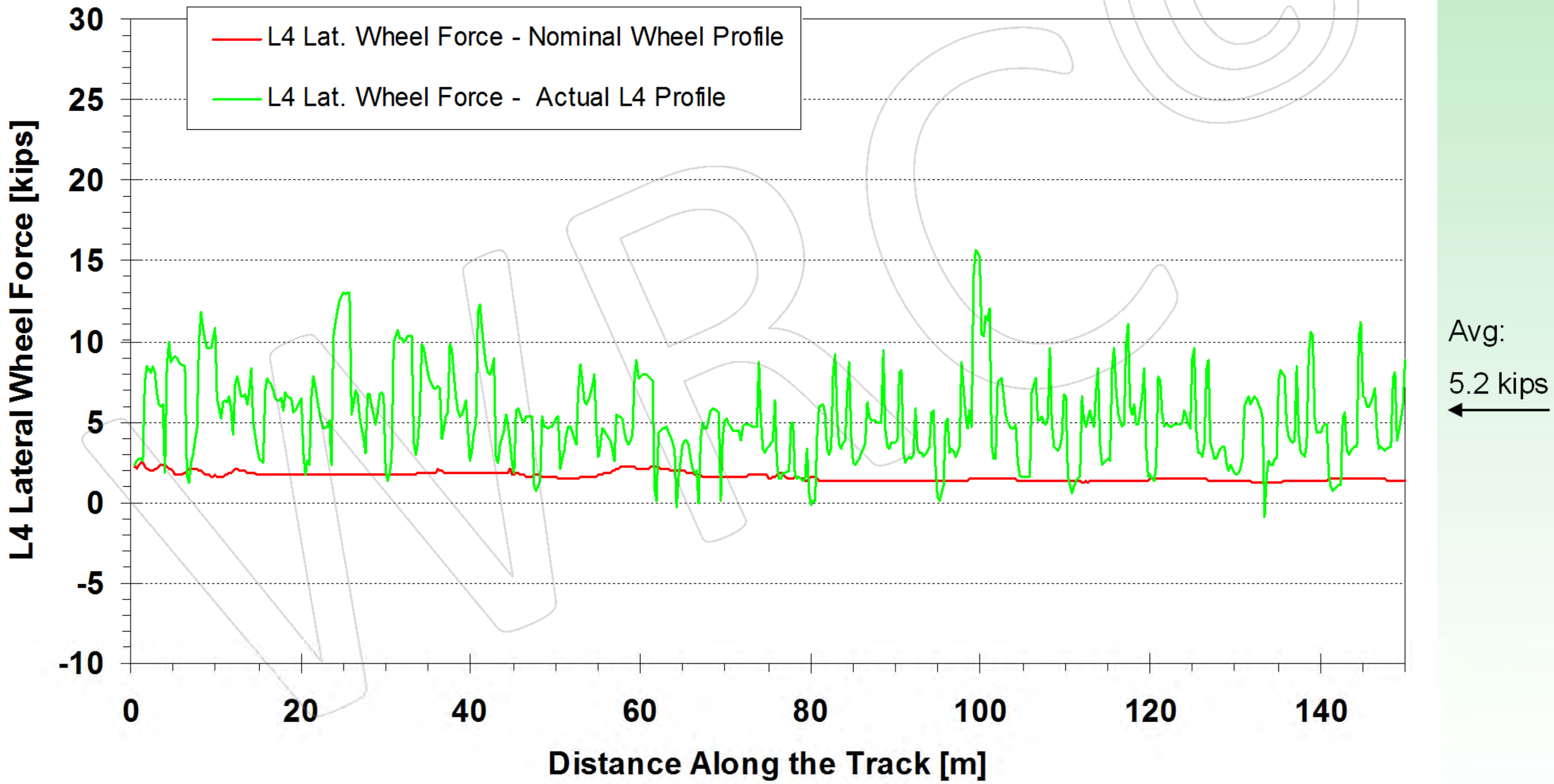


Vampire® Simulation Results
L4 Lateral Force



Vampire® Simulation Results

L4 Lateral Force in an ideal 6-deg RH Curve



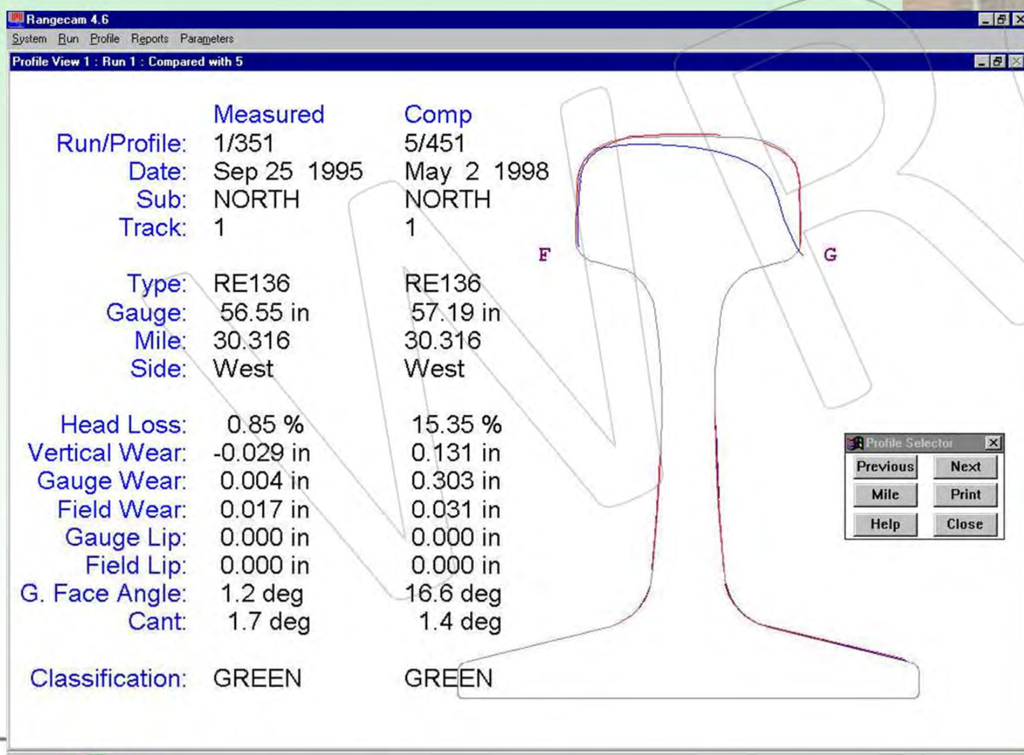
Miniprof to Measure Wheel & Rail Profile

LazerView

Hand Held Laser Wheel Profiler

ARM

Optical Rail Measurement



Conclusions

- Simulation modeling is mature and well validated
- Simulation is more cost effective than physical testing
- Simulation is excellent tool for design and analysis
- Simulation modeling is well suited to help solve a variety of wheel/rail interaction issues
- Simulation is only a tool; there is as much *art* as there is *science* in mastering simulation analysis
- Don’t let simulation ever supplant common sense and experience