Paper #

Predict OTR Tire Deflection and Temperature

By Leighton Spadone*
DAAS Inc., Tire Technology and Data Analytics
Beachwood, OH

Presented ITEC Technical Meeting
Akron, OH
September 13-15, 2018

* Speaker

Abstract

Deflection-MPH: Predict Off-The-Road Tire Deflection and Temperature

Introduction:
A mine site's two largest operational costs are vehicle fuel and tires. Tire longevity is improved by limiting tire temperatures to the manufactures guidelines by limiting the tire's combination of speed, load, and inflation.

Deflection is the tire section height decrease as can be measured from the center of the tire rim to the road surface due to a tire Load at a tire Inflation pressure. Deflection is a function of the tire load@inflation combination.

Predicting radial OTR Tire deflection and footprint dimensions reduces deflection-testing needs and the response time for deflection feedback. Model predictions can provide data across a wide range of loads and inflations that are not normally tested.

Measuring deflection simplifies and accurately reflects the tire load and inflation that is needed to Model the Tire's Equilibrium Running Temperature and Deflection.

Benefits:
Predicting tire deflection and footprint dimensions, allows tire footprint dimension optimization to meet vehicle requirements at an early design stage, before investment in molds and tire production.

Modeling Tire Deflection and Tire Running Temperatures provides an accurate methodology, Deflection-MPH, to predict tire overheating.

At mine sites, TMPH calculations use estimates of tire load based on assumptions of vehicle weight, haul load and load distribution to each tire and assumptions about each tire's inflation pressures. Errors in these estimates can lead to tires being over-deflected and generating running temperatures that exceed their manufacturer's recommendations. The TMPH equation is not predictive of tire equilibrium running temperature.

The ability to model tire deflection and running temperatures allows the implementation of Deflection-MPH equations that can match tire running temperature to vehicle service conditions in order to limit tire overheating and heat related failures and removals.

Predict OTR Tire Deflection

Introduction:

A mine site's two largest operational costs are vehicle fuel and tires. Tire longevity is improved by limiting tire maximum temperatures to the manufactures guidelines by balancing the tire's operational speed, load, and inflation combinations. Maximizing mine profits depends on balancing tire replacement and vehicle downtime costs vs. tonnage and profits.

The mining account vehicle work cycle consists of a loaded and empty round trip cycle. The Job or Vehicle TMPH is defined as the average, loaded plus empty, vehicle load in Tons multiplied by the average speed in MPH. The individual tire inflations and individual tire loads are not included in the TMPH calculations, only the vehicle total loads. Therefore, TMPH assumes each individual tire load and inflation is correct. Further, the TMPH equation is not predictive of tire running temperatures.

It is the tire's deflection, as it rotates thought the tread footprint area @MPH, which causes the tire to flex, compress, and generate heat. The tire heat build-up is due to Deflection-MPH and so Deflection-MPH, is the actual limiting factor for a tire's actual heat performance. The individual tire's running temperature is critical to tire longevity.

The Challenge:
Critical OTR Tire compound properties like strength, adhesion, and tear performance are reduced by tire temperature buildup, which in turn, increases the tire's vulnerability to cutting, tearing, bruising, penetrations, and component separation in service.

At the mine sites, individual tire loads are usually estimated from the vehicle weight, the payload, and the assumed payload distribution. The vehicle weight and weight distribution varies across vehicle models and model revisions. These assumptions can lead to systematic tire load estimate errors that can lead to overheating individual tires.

The Tire and Rubber Association, T&RA, tire inflations are specified at "Cold" or the ambient temperature. Since many mines operate 24/7, periodic tire inflation checks are not accurate since they depend on the actual ambient temperature, the increase in inflation pressure due to the in-service tire's air-cavity temperature-pressure rise, and due to any undetected pressure leaks. A running tire's "Hot" inflation pressure check is not easily interpolated back to Cold-Ambient inflation conditions, even when the Ambient Temperature is known for a given time of day. Accurate "Cold" T&RA inflation pressures of in-service tires are generally unknown.

For a given tire in service on a vehicle, measurements of deflection and speed provide information to predict the tire's temperature performance capability without relying on estimates of individual tire load and inflation.

Measuring vehicle tire deflections at a known load, like at the empty vehicle weight during fueling, can be used to set correct tire inflations regardless of ambient temperature, pressure leaks, or in-service tire inflation pressure increases due to tire air cavity heating.

Strategy:
Model and predict OTR tire Deflection across a range of loads and inflations.

Model and predict OTR tire "Ambient Temperature Corrected, Equilibrium Temperatures."

Use the **Deflection-MPH** to avoid overheating and removing tires prematurely.

OTR Deflection Models:
OTR mold dimensions for 224 radial OTR sizes & types were merged with 4228 OTR static Load-Deflection tests, resulting in 4188 lines of data available for modeling. About 10% of this historical data was internally inconsistent and they were either discarded or corrected.

Model Limitations:
The Deflection Dataset uses a Single Brand of tires. The Dataset size for the Footprint models is 104 observations and for Equilibrium Temperature model is 155 observations.

Deflection Model Dataset:
Table 1: Range in Dataset of Tire Mold Dimension: Bead Diameter, Section Width, Section Height, Rim Width, Outside Diameter, and Non-Skid Tread Depth (Inches).

BD_DIA			SectW_S		SEC_H		RIM_W		Spec OD		NS_IN	
N	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
4188	20	57	14.65	44.6	12.5	41.75	9.5	36	50	140.5	0.978	4.76

Figure1: Distribution of Tire Bead Diameters in the Dataset

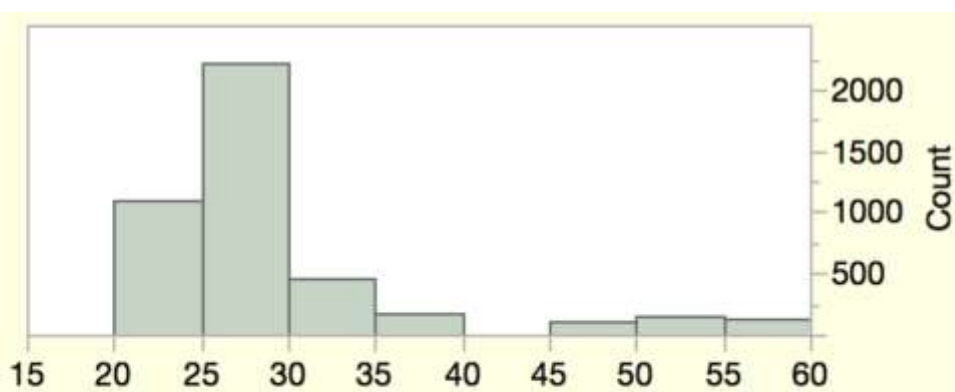
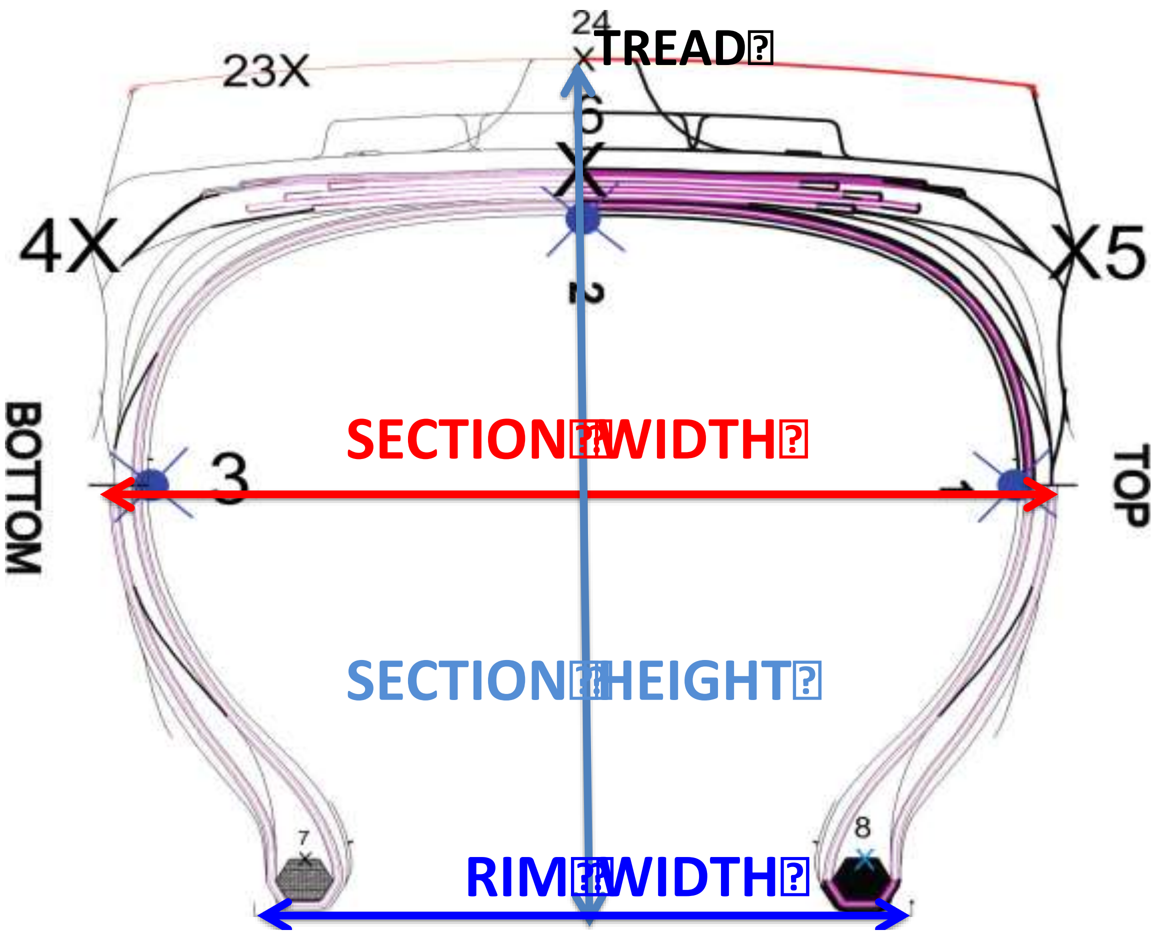


Figure2: OTR Tire Cross-Section



Deflection Modeling Methodology:
The maximum **Load Capacity@PSI** of each tire size and type was calculated using the static deflection test's **Load and Inflation** and the tire **Mold Dimensions** using a public domain **Load-Capacity-Formula**. The **Percent Deflection of the Section-Height** was modeled as a function of the **Load as a percent of the Formula's Load Capacity** at test **Inflation PSI**.

Figure 3: Simple Model Regression Plot of Percent Deflection of the Section-Height

Actual by Predicted Plot

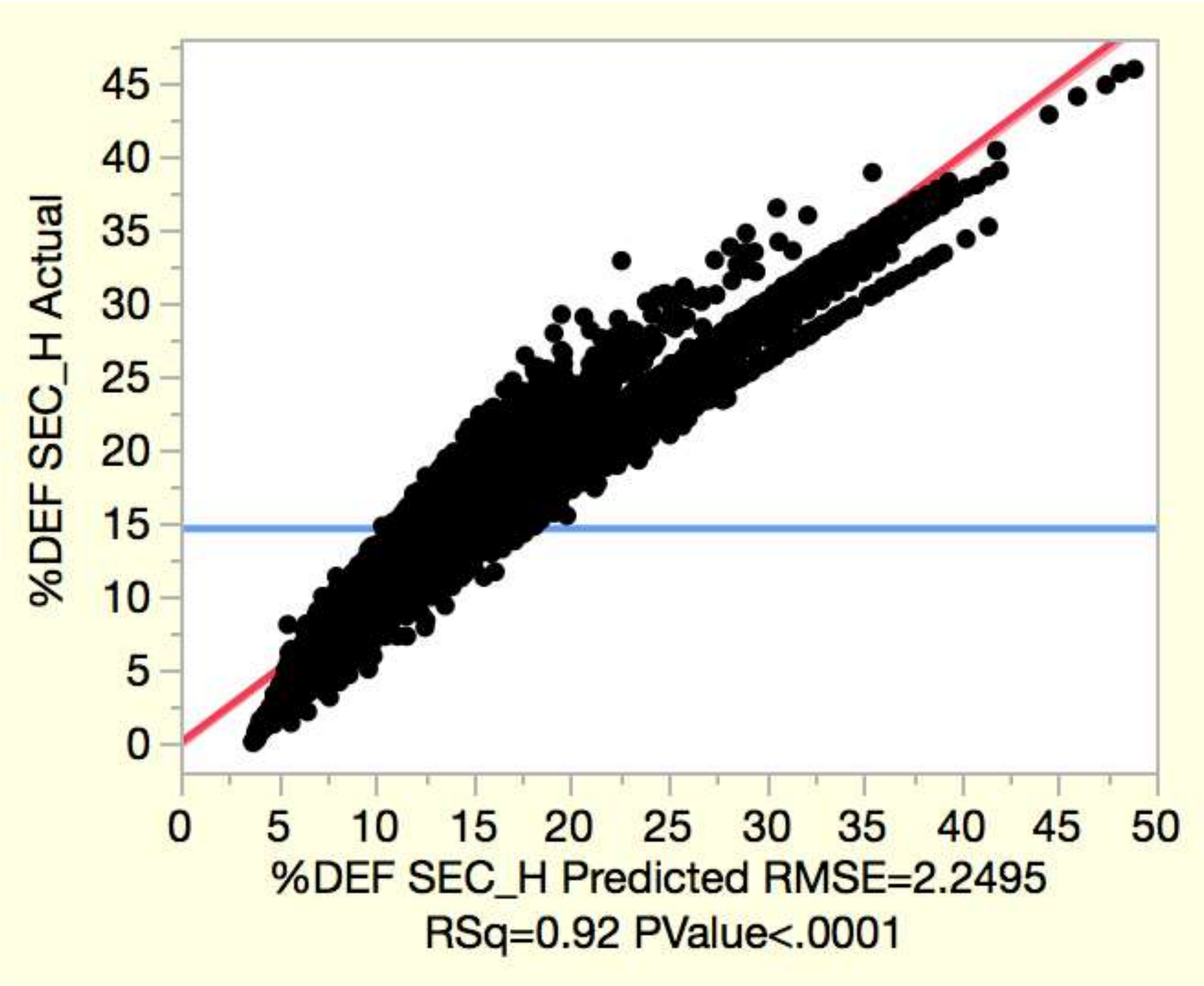


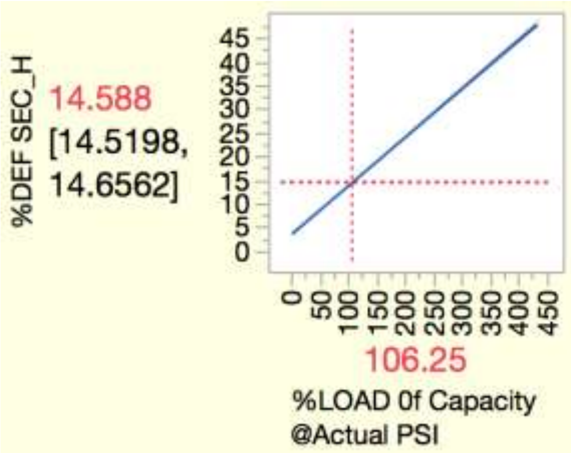
Table 2: Simple Model Factors Effects and Significance

Effect Summary

Source	LogWorth		PValue
%LOAD 0f Capacity @Actual PSI	2342.433		0.00000

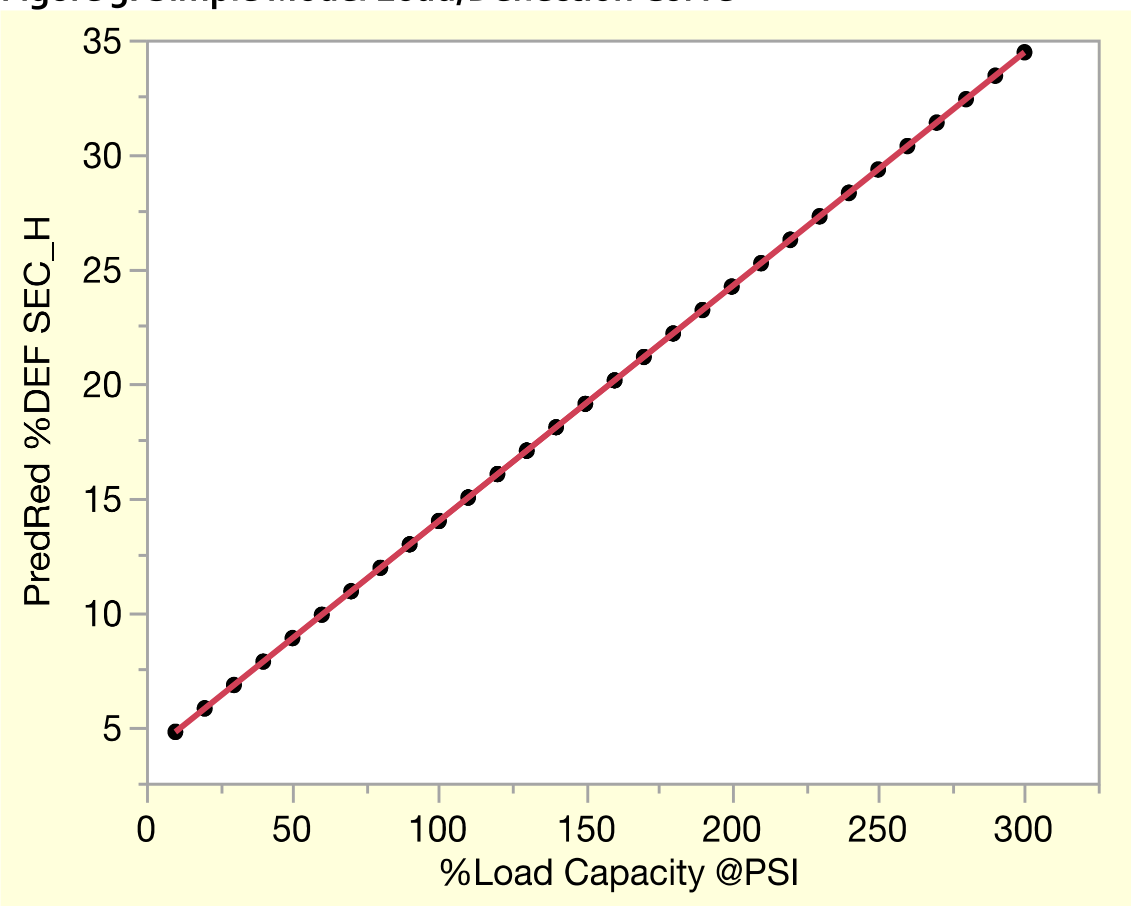
The Prediction Profiler below, is a graphical, dynamic representation of the model that allows changing the input parameter using sliders in Figure 4 below. (Red).

Figure 4: Prediction Profiler Snapshot of the Simple Model %Deflection Predictions



Since the predictors in the model are specified as Ratios: **Deflection as a Percent of Section-Height** and the **Load as a Percent of the tire's Load Capacity** across a range of Inflation pressures, this single %Deflection curve is useful across a range of Relative Loads @ Inflation pressures. This model is referred to as the "Simple" since it uses only one predictor.

Figure 5: Simple Model Load/Deflection Curve



Implementation:

A JMP Data Table Template containing the mold dimensions, regression equations, and load capacity formulas allows substituting actual mold dimension in desired units in place of these relative dimensions and can be used to generate actual load/deflection/inflation values that can be plotted as deflection curves and provide specific deflection values at a load@inflation.

Template Factors

Mold Dimensions

- **MPH & PSI**
- **SEC_H**
- **Ref OD**
- **NS_IN**
- **N_G**
- **SectW_S**
- **BD_DIA**
- **RIM_W**
- **TREAD AREA**

Calculations

- **STEP PSI**
- **STEP LOAD**
- **Load Capacity @PSI**
- **Pred %DEF SEC_H**
- **Predict DEFL_INCHES**
- **K@ 5MPH or 30MPH**
- **PredFPLen %TrdArea In^2**
- **PredFPArea %TrdArea In^2**
- **PredFPWidth %TrdArea In^2**
- **PredAmbientCorrectedTempF**

Below in Figure 6, is a more specific, slightly better fitting model, where the RSquare fit increases from .92 to .94. In order to use this Specific Model, a JMP Data Table template must be created for each individual tire size and type, since the tire mold tread pattern Non-Skid and tire mold Outside Diameter have been added to the Simple model's predictors.

Figure 6: Specific Model Regression Plot of Percent Deflection of the Section-Height

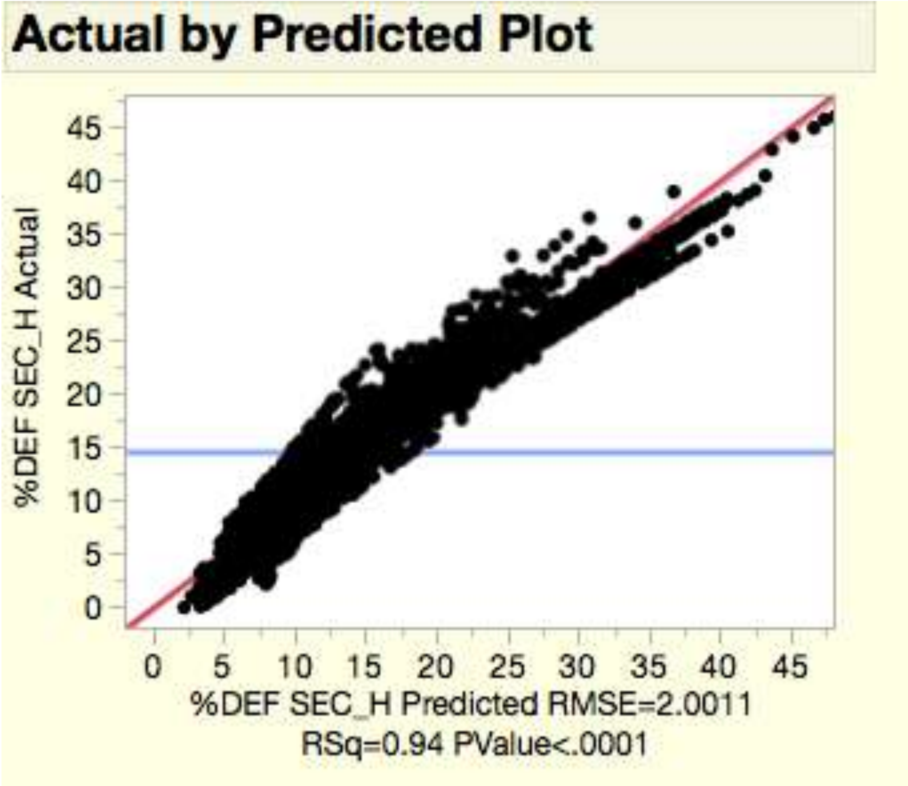


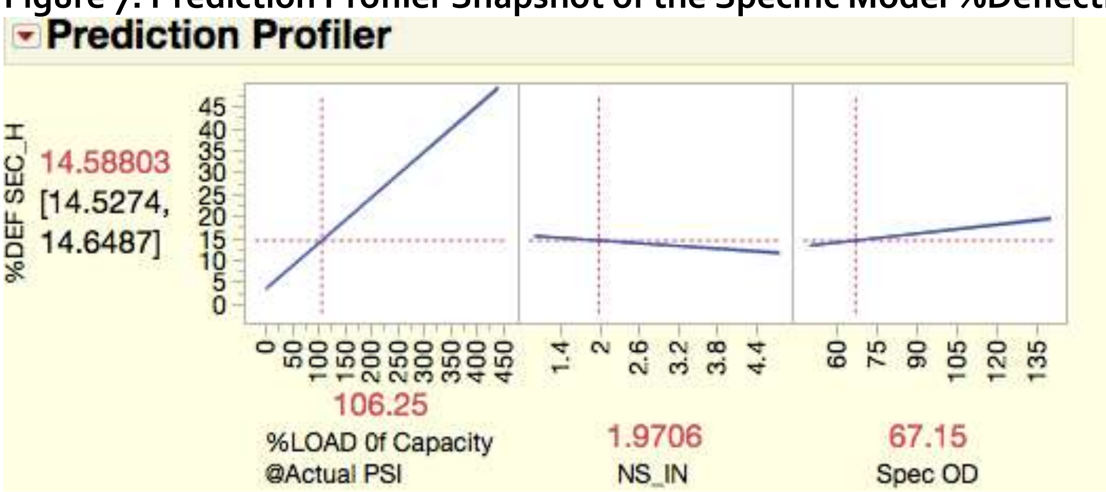
Table 3: Specific Model Factors Effects and Significance

Effect Summary

Source	LogWorth		PValue
%LOAD 0f Capacity @Actual PSI	2552.769		0.00000
Spec OD	212.937		0.00000
NS_IN	114.738		0.00000

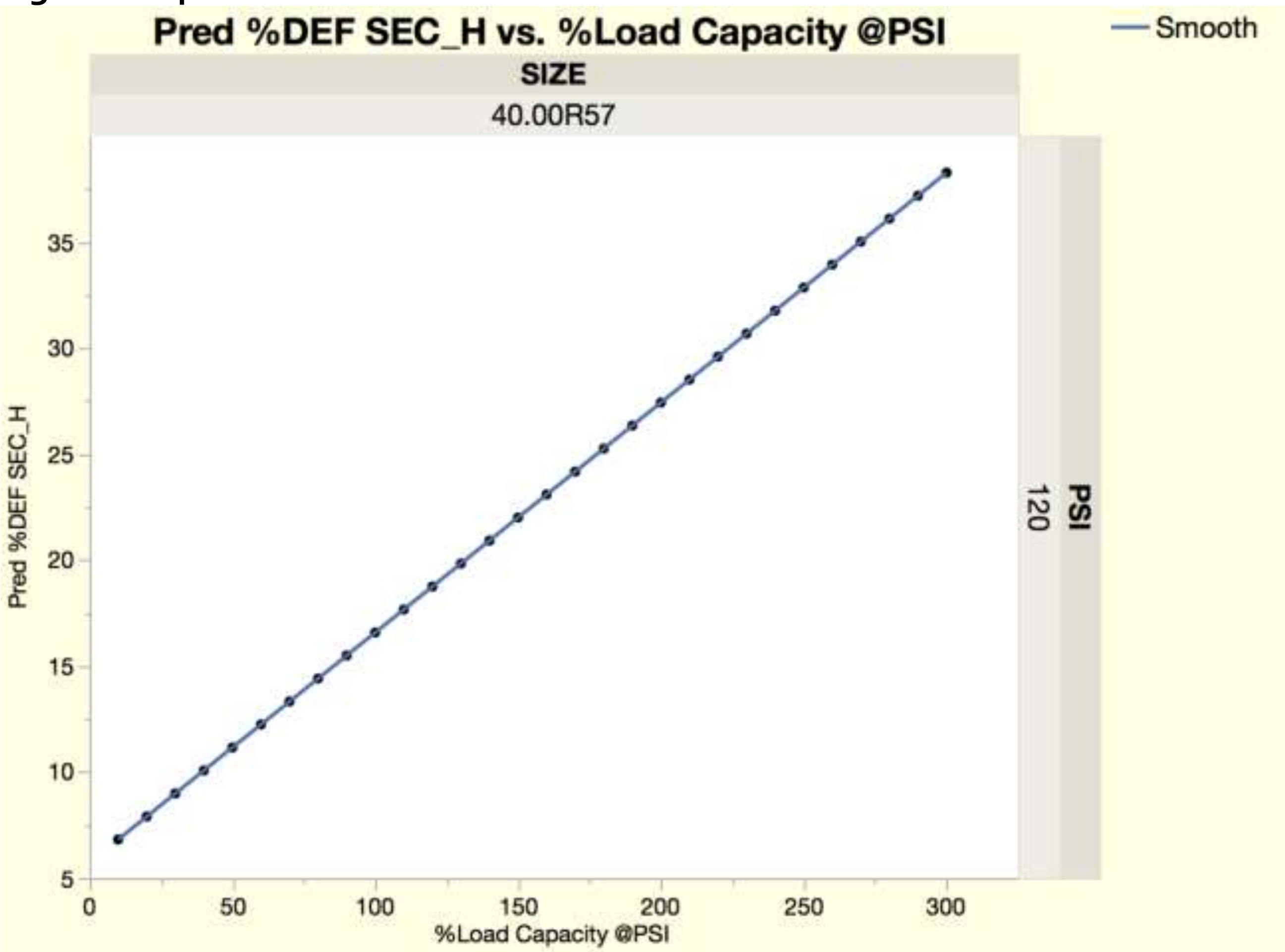
The Load Capacity @ specified PSI, the Non-Skid, (NS_IN), and the Specified Mold Outside-Diameter, (Spec OD) predicts the %Deflection of the tire's Section Height.

Figure 7: Prediction Profiler Snapshot of the Specific Model %Deflection Predictions



For example, using the 40.00R57 mold dimensions in the dataset and the Specific %Deflection equations, a relative load-deflection-pressure curve can be generated as shown in Figure 8. The intercept of the Specific model differs slightly from that of the Simple model.

Figure 8: Specific Model Relative Tire Deflection Curve for all Inflation Pressures



The Model Effects for the Non-Skid, N_S, and the Specified Mold Outside Diameter, OD, are relatively minor contributors to the deflection model as compared to the %Load of Capacity @ Actual PSI. The Simple Model, Figure 3, does not include these two factors from the model, and therefore can provide a single, relative Load-Deflection Curve that is applicable across all OTR tire sizes and types.

Sacrificing some model fit by using the Simple Model provides a single OTR, size-type-universal, relative Load-Deflection Curve! The RSquare Fit for the Simple Model is 0.92 and maintains a predictive accuracy of about ± 0.05-percentage points error range. This fit and predictive accuracy should be adequate and would simplify calculations at the mines.

Footprint Models:

Tire footprint width, length, and area predictions were each modeled on a 104-observation dataset. Their models feature the %Deflection Predictions as a factor in some Footprint

Models to estimate the footprint dimensions. The Tread Width model is not dependent on the Specific Deflection model equation.

These footprint models are also use relative or ratio factors. That is, Footprint length, width, and area are modeled as a percentage of the Tire Mold's Tread Area. The Mold Tread Area is standard mold dimension that is a function of the Section Width, SectW_S, the Tread Outside Diameter, OD, and the Bead Diameter, BD_DIA.

Mold Tread Area Dependencies

Figure 9: Mold Tread Area Model

Actual by Predicted Plot

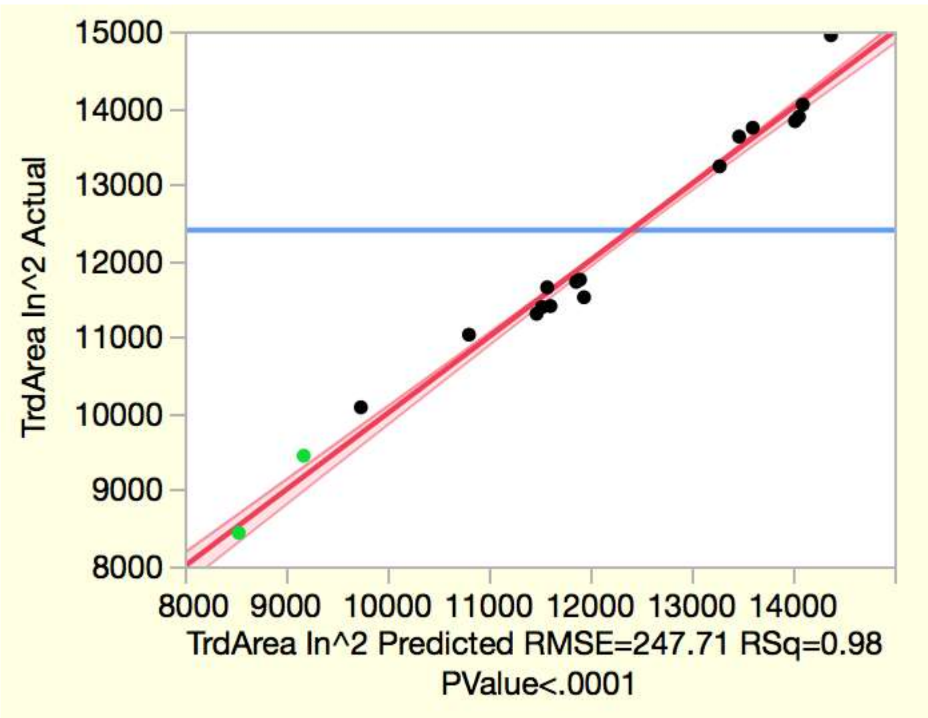


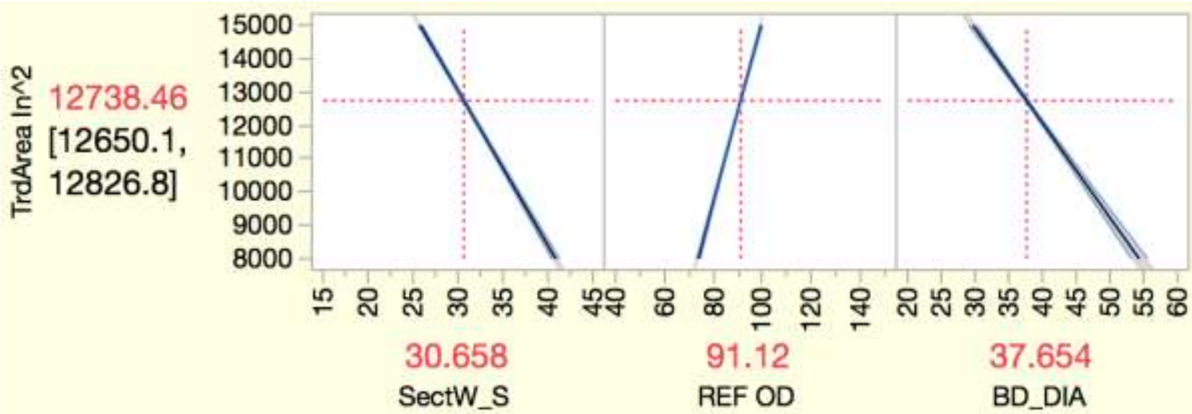
Table 4: Mold Tread Area Model Factors Effects and Significance

Effect Summary

Source	LogWorth		PValue
SectW_S	74.302		0.00000
REF OD	69.750		0.00000
BD_DIA	49.581		0.00000
REF OD*REF OD	14.009		0.00000

Figure 10: Mold Tread Area Model Predictions Snapshot

Prediction Profiler



Footprint Length Model

Figure 11: Footprint Length as a percent of Tread Area

Actual by Predicted Plot

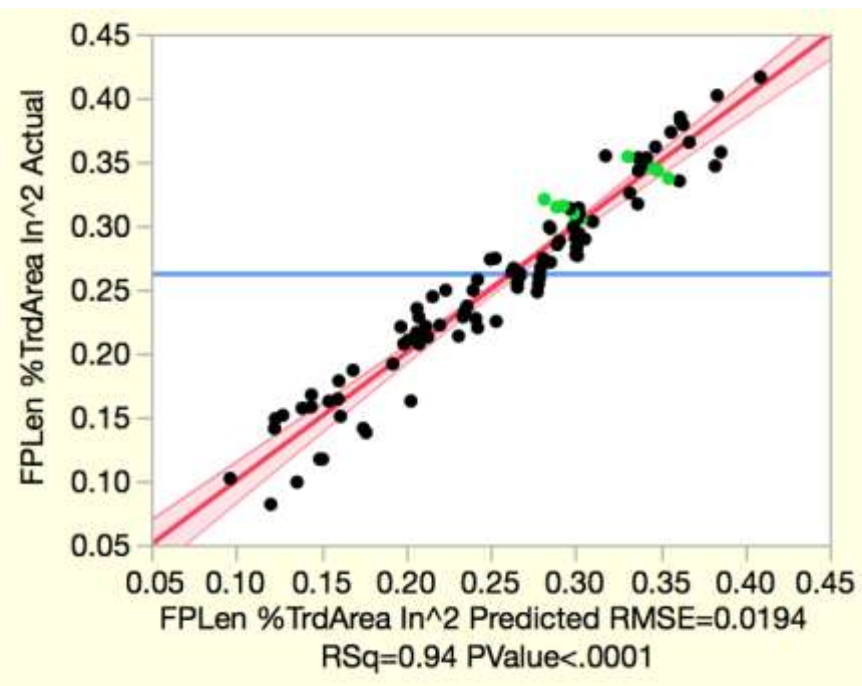
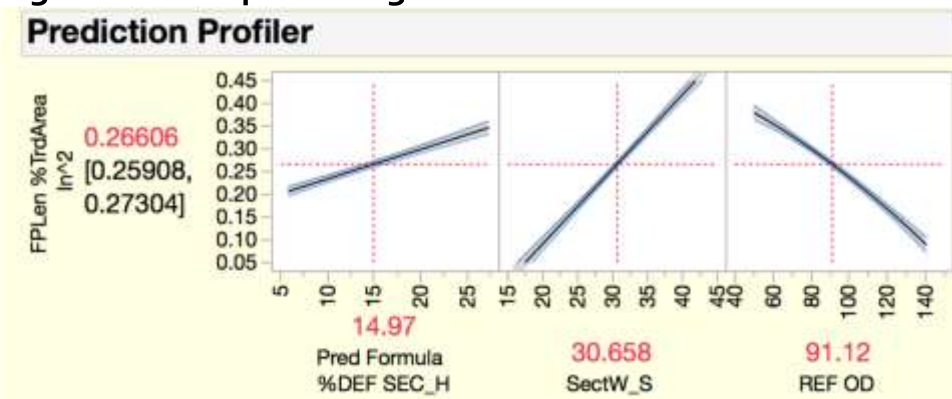


Table 5: Footprint Length Model Factors Effects and Significance

Effect Summary

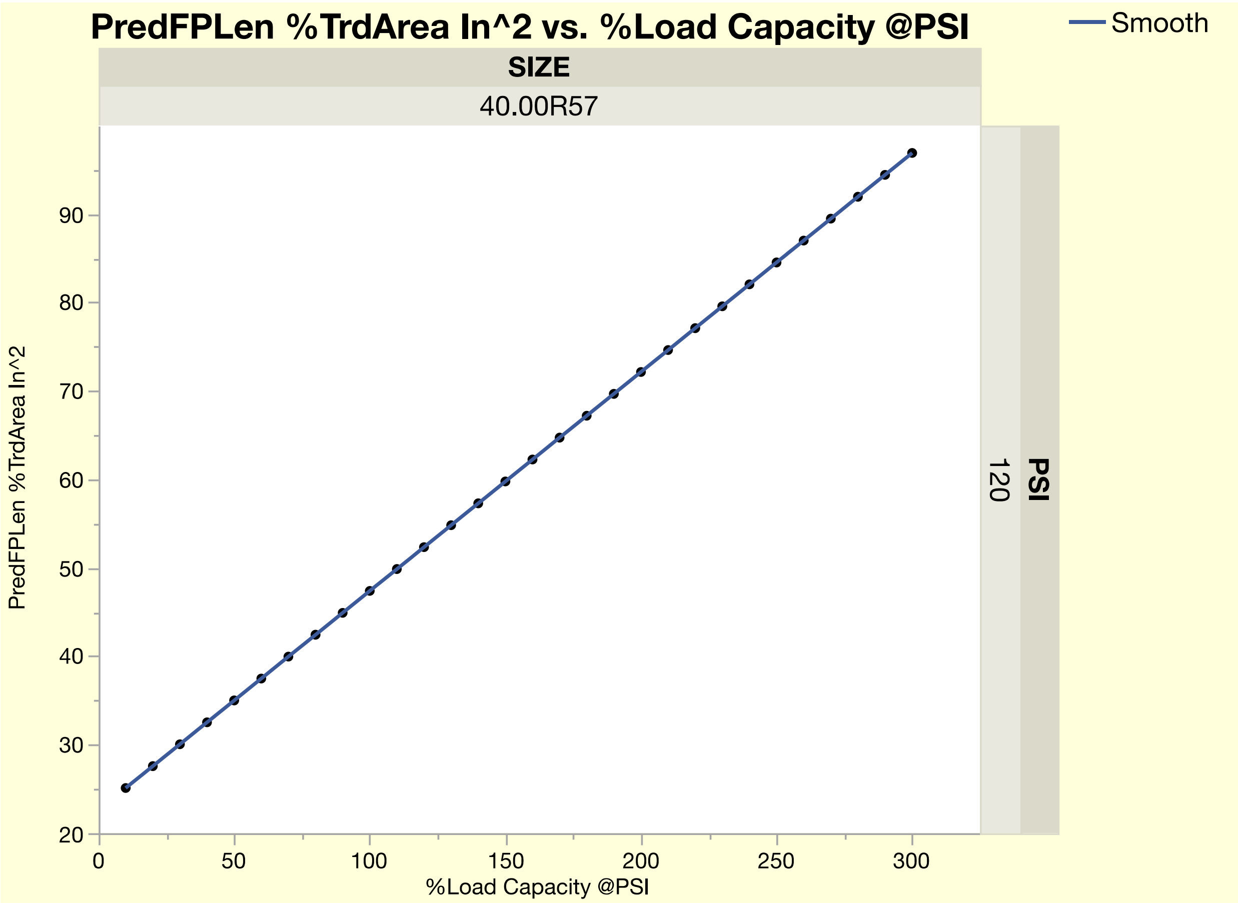
Source	LogWorth	PValue
SectW_S	45.467	0.00000
REF OD	32.583	0.00000
Pred Formula %DEF SEC_H	23.256	0.00000
Pred Formula %DEF SEC_H*REF OD	18.065	0.00000
SectW_S*Pred Formula %DEF SEC_H	9.128	0.00000
REF OD*REF OD	2.301	0.00500

Figure 12: Footprint Length Model Predictions



The model for **Footprint Length as a Percentage of the Mold Tread Area** is only partially dependent on the **Percent of Load Capacity at Inflation PSI** factor as can be seen in Table 5. The **Footprint Length %Tread Area Curve** vs. the **Percent of the Load Capacity** in Figure 12 is valid only for each Specific Model mold dimensions across all inflation pressures.

Figure 13: 40.00R57 Footprint Length as a Percent of the Mold Tread Area vs. Percent of Load Capacity.



Footprint Area Model

Figure 14: 40.00R57 Footprint Area as a Percent of the Mold Tread Area vs. Percent of Load Capacity that is valid across all Inflation Pressures.

Actual by Predicted Plot

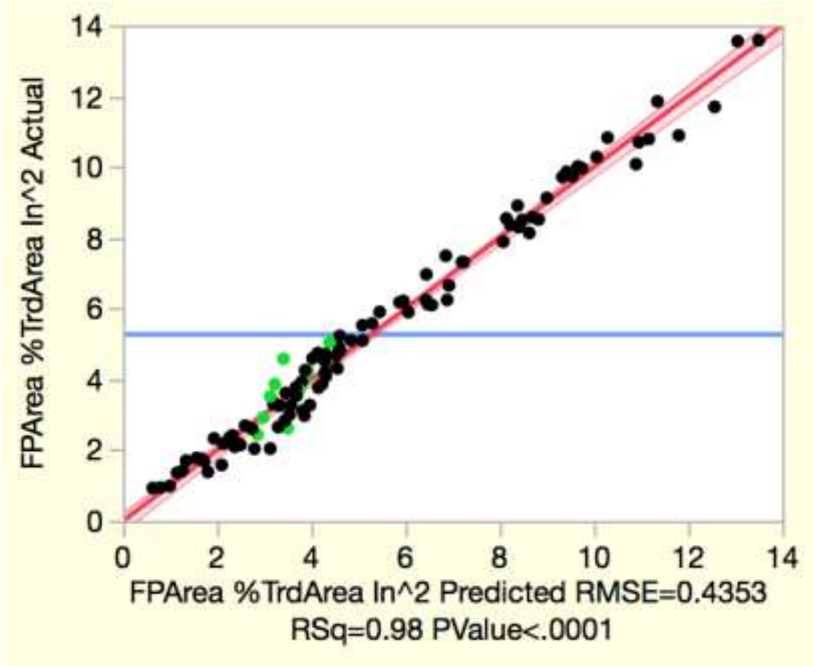


Table 6: Footprint Area Model Factors Effects and Significance

Effect Summary

Source	LogWorth	PValue
Pred Formula %DEF SEC_H	48.921	0.00000
SectW_S	33.179	0.00000
Pred Formula %DEF SEC_H*REF OD	27.682	0.00000
REF OD*REF OD	13.837	0.00000
REF OD	4.276	0.00005 ^

Figure 15: Footprint Area as a percent of Tread Area

Prediction Profiler

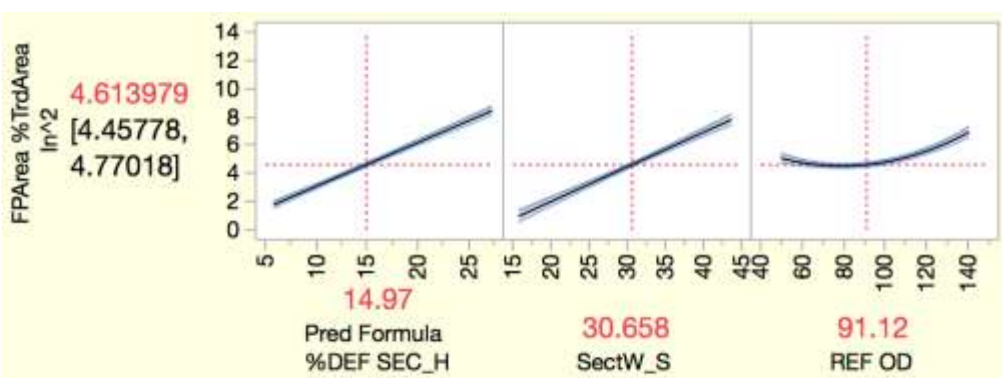
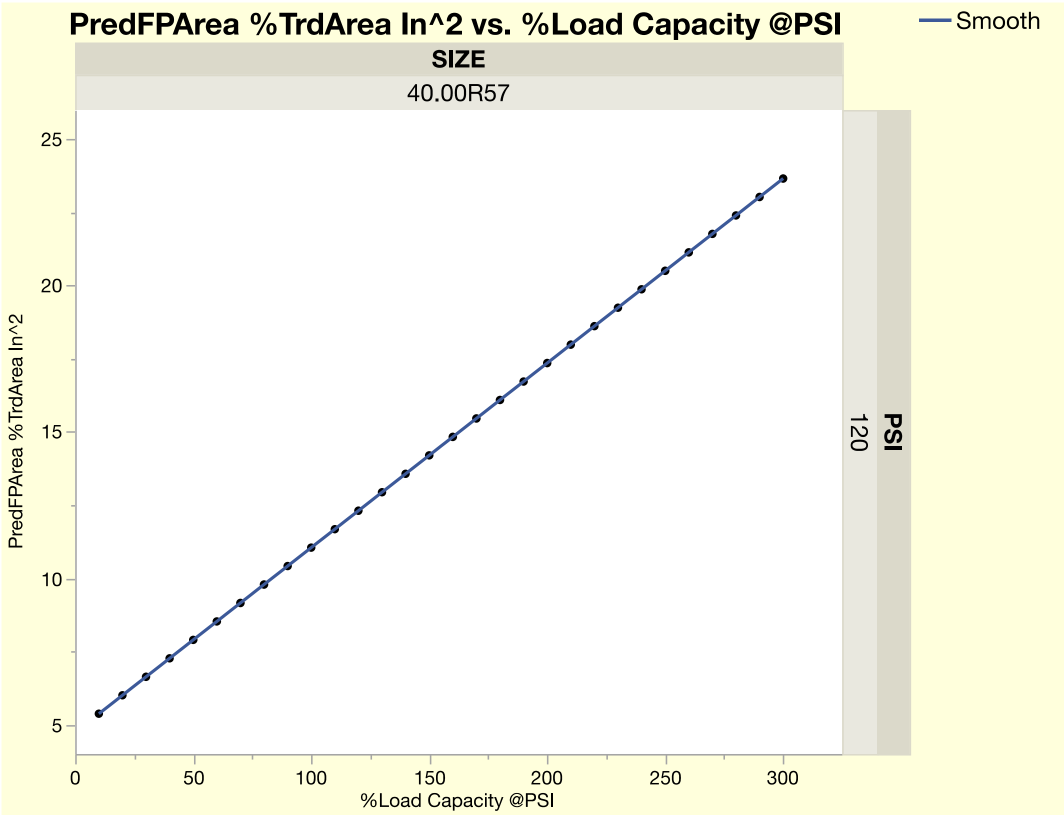


Figure 16: 40.00R57 Footprint Area as a Percent of the Mold Tread Area vs. Percent of Load Capacity.



Footprint Width Model
Figure 17: 40.00R57 Footprint Width

Actual by Predicted Plot

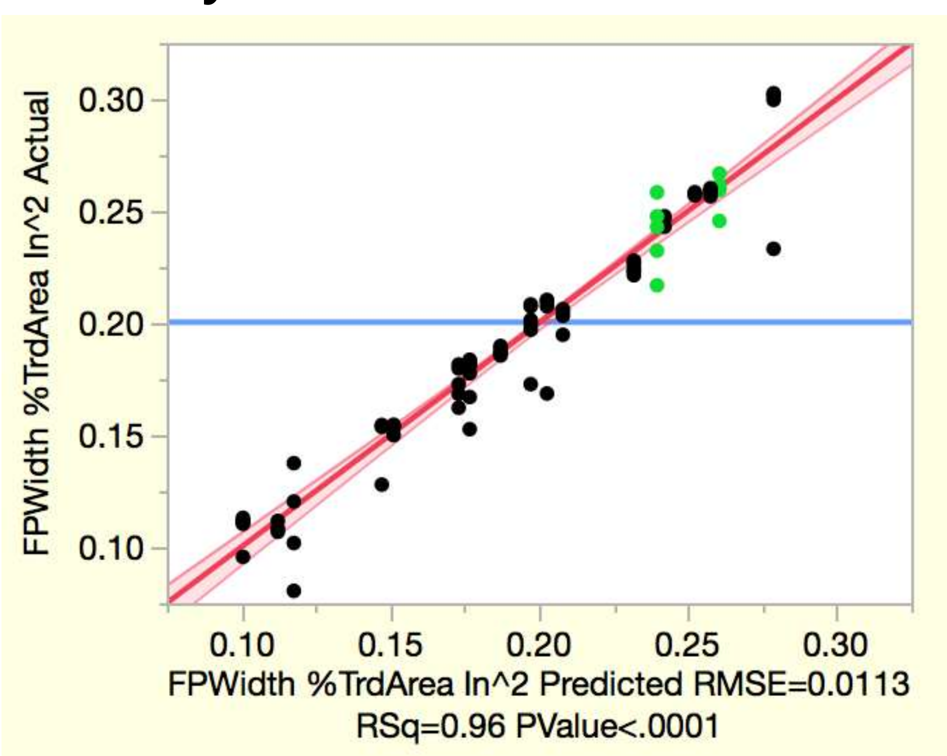


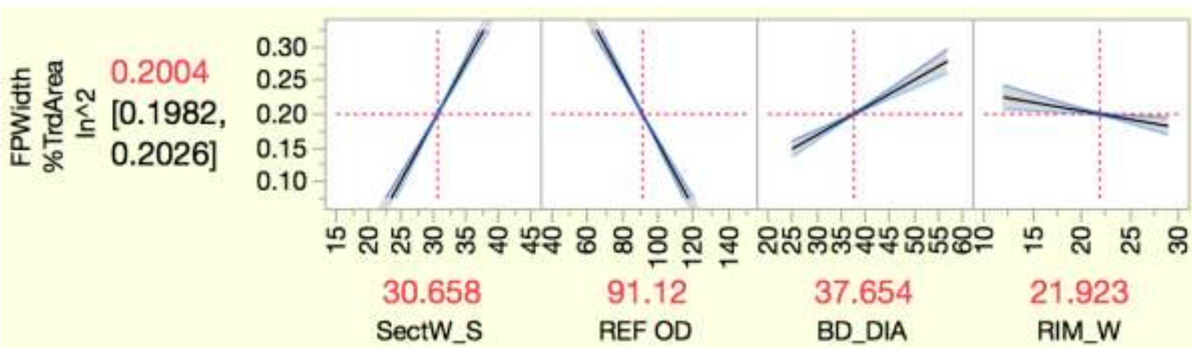
Table 7: Footprint Width Model Factors Effects and Significance

Effect Summary

Source	LogWorth	PValue
REF OD	32.942	0.00000
SectW_S	32.513	0.00000
BD_DIA	13.453	0.00000
RIM_W	2.237	0.00579

Figure 18: Footprint Width as a percent of Tread Area

Prediction Profiler



Footprint Width as a percent of Tread Area is not dependent on the Percent Deflection and therefore it does not vary across the Percent Load Capacity.

Tire Temperature Model

The model data consists of 155 OTR tire tests run to equilibrium temperature at T&RA specified load & inflation at various MPH. Only a single tire brand was tested

Table 8: Ambient Corrected, Equilibrium Temperature Model Predictors

Model Predictors Distribution

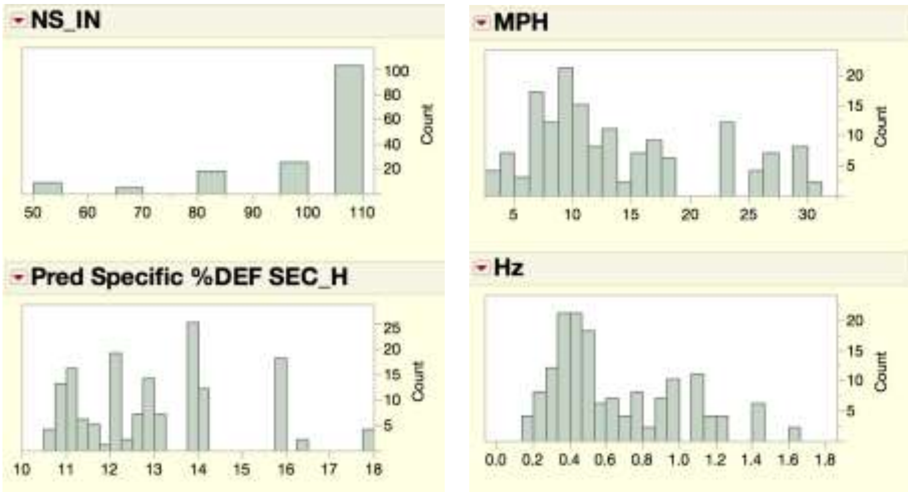
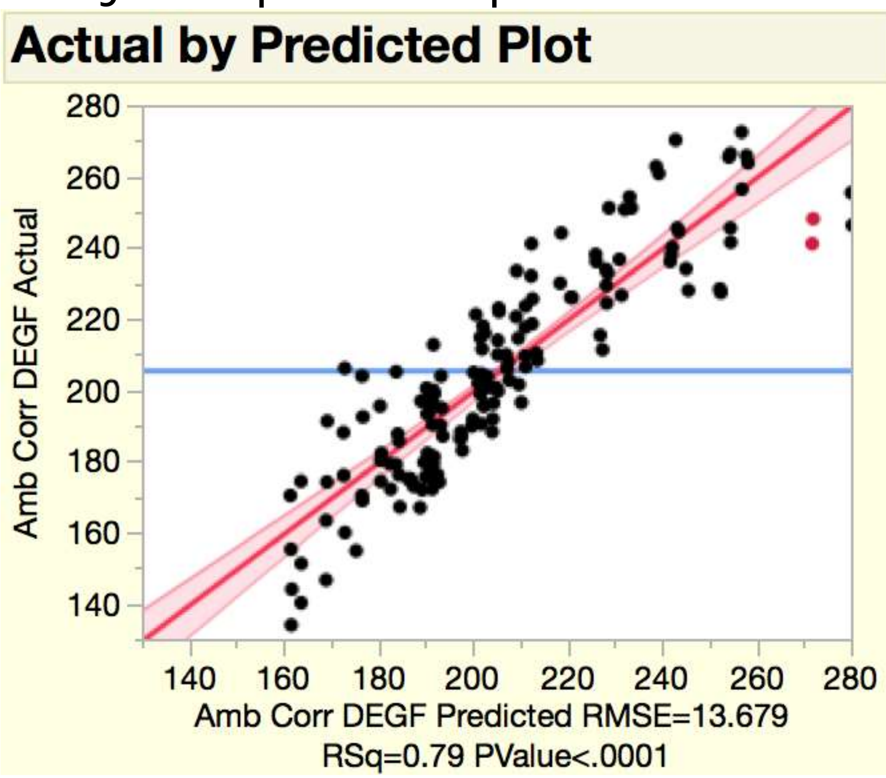


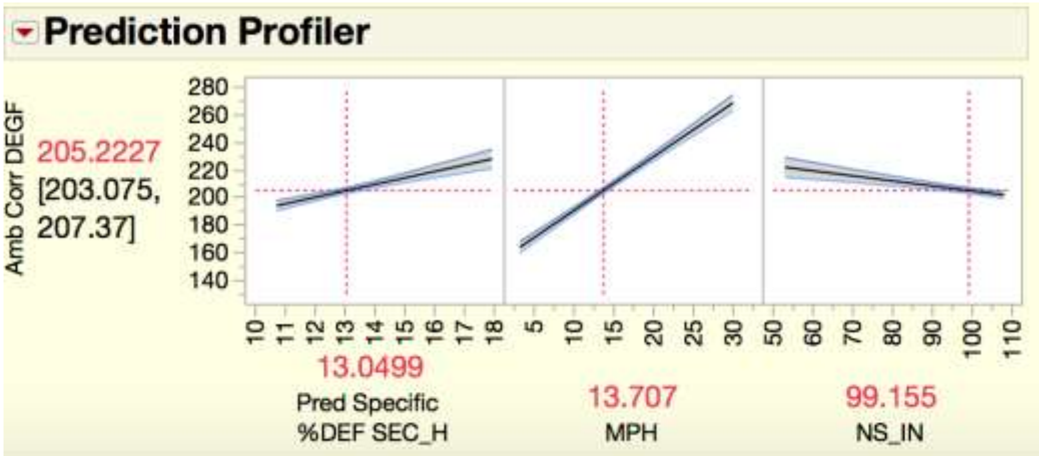
Figure 19: Ambient Corrected, MPH Equilibrium Temperature Model
Table 9: MPH Equilibrium Temperature Model Factors and Significance



Model Factors Effects and Significance

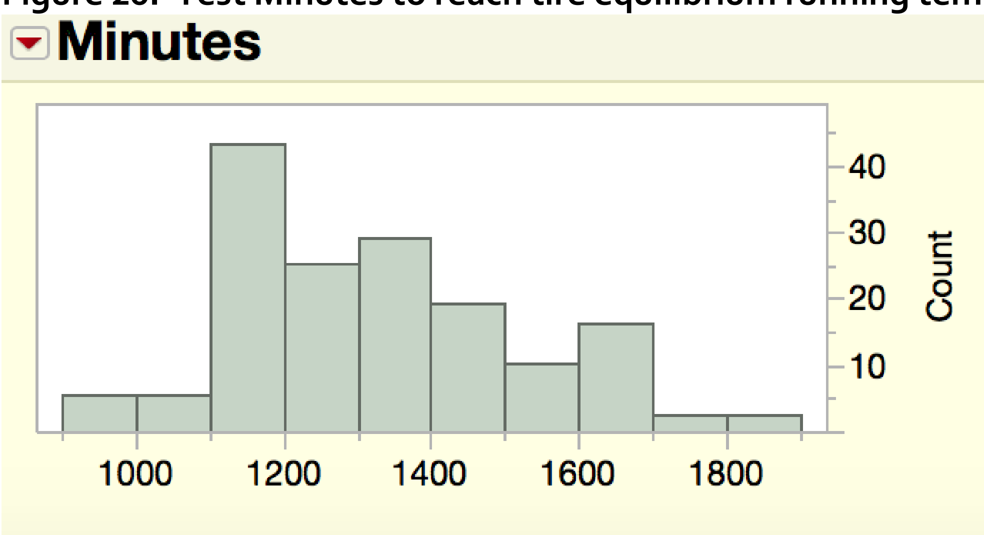
Effect Summary

Source	LogWorth	PValue
MPH	52.232	0.00000
Pred Specific %DEF SEC_H	9.958	0.00000
NS_IN	5.685	0.00000



Two similar models both predict tire equilibrium temperature as functions of speed (MPH or Hz), Deflection, and Non-Skid. These equations are preferred since tire inflation and load are included in the models as part of the Deflection predictor. The Deflection-MPH and the Deflection-Hz Tire Temperature Models have a fair accuracy with .79 RSQ fit and average predictive error of about ± 3 to ±8 DegF predictive error. These Predictions are based on tire equilibrium DegF that are reached after many minutes of continuous running and are more accurate for Mines running 24/7 operations.

Figure 20: Test Minutes to reach tire equilibrium running temperature.



Deflection-MPH Model Equation

Tire Equilibrium Ambient Corrected Temperature DegF: =
126.726 +
4.627 *: Pred Specific %DEF SEC_H +
3.937 *: MPH + -0.36 *: NS_IN
The deflection term, :Pred Specific %DEF SEC_H, includes the tire load and inflation, necessary to detect over-deflection situations.

Deflection-Hz Model Equation
Tire Equilibrium Ambient Corrected Temperature DegF: =
61.968 +
81.83 * :Hz +
3.504 *:Pred Specific %DEF SEC_H +
0.456 * :NS_IN
Hz is the cycles/sec of tire rotation, the (Revolutions/Mile * MPH)/3600 Sec/Hr

Deflection-MPH Development
OTR Tire heating data is available to model alternate Tire Temperature predictions at less than temperature equilibrium conditions, like at shorter times in the heating cycle.
Possibly, tire cooling rates applied during unloaded return hauls, could be added to the model to tailor temperature prediction accuracy to Mining Account operating conditions.

T&RA Standards Example:
The T&RA OTR Handbook Table CR-30 for a Conventional Transport Radial 30MPH rated 40.00R57, has a load capacity of 132,500 pounds at 102 PSI "Cold" inflation and has an Excess Load Allowance of +7% at a +14% inflation or 142,000 pounds at 120 PSI "Cold" inflation.

The Deflection Model predicts a maximum deflection of a fully loaded 40.00R57 tire to be about 15.5% of the Section Height at the T&RA maximum load and cold inflation pressure per above.

The predicted Ambient Temperature Corrected DegF tire temperature at the T&RA 30 MPH Standard is 287F ± 8 DegF compared to the Tire Industry Maximum Tire Temperature Guidelines that range between 203F-221F. The predicted value is about 60 DegF greater than the guideline range. T&RA OTR Dimensional Design, Load, Inflation, and MPH standards would allow a tire to overheat.

Summary:
Tire Deflection measurement is simple, fast, and accurate and avoids using estimates of cold inflation pressure and Vehicle weight, load, and load distribution as used by TMPH.

Two model versions for tire Deflection and for Ambient Corrected Tire Equilibrium running temperature were developed. Together these equations provide a guideline to control tire temperatures in service.

Model fits for tire deflection and their predictive accuracy were excellent.

Model fits for tire footprint dimensions and their predictive accuracy were excellent.

Model fits for tire running temperature were fair and their predictive accuracy was fair.

Reliance on T&RA Standards or the TMPH System can result in tire overheating and increased vunerability to component separation and hazards damage.

Results:
Combining Tire Deflection and Tire Equilibrium Temperature equations provide a guideline to control tire temperatures in service.

Modeling Deflection as a ratios, deflection as a percent of tire section height predicted by load as a percentage of tire load capacity, results in a single Simple Model load-deflection curve that is useful across all tire inflation pressures and across all the sets of OTR tire sizes and types of mold dimensions in the dataset.
Tire Footprint Dimensions were modeled as ratios of length, width, and area as a percentage of the mold tread area and were useful across all inflation pressures but only within each specific set of OTR tire sizes and types of mold dimensions in the dataset

Benefits:
The ability to model Tire Deflection and Ambient Corrected Equlibrium Temperature across OTR sizes and types makes it practical for a mine to implement Deflection-MPH equations to avoid overheating tires that leads to increases in tire removals.

These modeled OTR tire deflection and footprint dimension predictions are easily implemented for any measurement system and enable the use of the Deflection-MPH and Equilibrium Temperature model equations to avoid overheating and damaging tires in service.