TIRE SHOULDER WEAR
IN REPETITIVE ROLLOVER TESTING

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ABSTRACT

The effect of tire shoulder wear on a vehicle's lateral acceleration and on the most-loaded tire's lateral deformation in 19 identical severe maneuvers was found to be negligible, at least for the vehicle/tire (2001 Chevrolet Tracker with OEM Uniroyal Tiger Paw AWP tires) measured. The test maneuver was the "ATI Reversed-Steer",with 180 degrees left/180 degrees right at 50 mph, generating a sustained lateral acceleration of 0.83 g.

INTRODUCTION

The question of how tire shoulder wear affects vehicle performance in repetitive rollover tests was first noticed in 1971, in research performed by the University of Michigan for NHTSA[1]. For some of the square-shouldered bias-ply tires current at that time,the maximum tire sideforce was found to increase drastically (as much as 40 percent) in sequential limit steer runs, until leveling off after 20-40 runs as the shoulders wore round. Some tires showed little or no increase after 20 runs (the Volkswagen 5.50-15 Conti), and some tires showed a small decrease (the Mercedes 7.35-14 Firestone and the Lotus 155HR13 Dunlop).

A conclusion of the Michigan research was that "It appears that adequate measurements of original equipment limit-cornering performance cannot be made for certain tire-vehicle systems by a testing method that utilizes repetitive runs as a means of searching for the limit, since the testing process acts to alter the original equipment condition".

At the present time almost all tires are radials, which do not seem to be severely affected by shoulder wear. Testing during the past three years in which repeated reversed-steer runs search for a tip-up threshold shows little effect of tire changes. It has become entirely practical to locate the threshold in a search protocol of 8-10 runs; then to perform "definitive" threshold measurements with unworn tires. Nevertheless, some critics have claimed that this process remains untenable because of tire wear. The study described herein is therefore designed to document the effects of tire shoulder wear on limit performance.

The study covers the behavior of one vehicle, the 2001 Chevrolet Tracker, with its OEM tire, the Uniroyal "Tiger Paw APW", GM TPC Specification 1031 MS, with cold inflation to the Placard-recommended 26 psi. (Figures 1 & 2).

ORGANIZATION OF THIS REPORT

This report is organized into two "paper" volumes, plus videotapes from vehicle interior and roadside cameras and CD's containing all raw and processed data. The vehicle interior video is the primary record, containing all raw data in 12-bit offset binary form, the "driver's view" and voice commentary. Volume 1 contains text, photos, trend plots, and references. Volume 2 contains time history plots of all of the processed data.

TIRE BEHAVIOR STUDIED

There are two principal aspects of tire performance which affect rollover: the ability to generate cornering forces; and the lateral deformation under side load which reduces the "half-trackwidth" of the vehicle. The degree to which these factors are affected by shoulder wear in repetitive test runs was the primary research question in this investigation.

TEST INPUT

The steer input chosen was a fully-automated "ATI Reversed-Steer"[2], using the Heitz Programmable Steering Machine (Figures 3 & 4). The vehicle is brought to a speed of at least 53 mph in a straight line, then the throttle is released. When the vehicle slows to 50 mph, the steer program begins automatically. The steer is ramped to 180 degrees left at 600 degrees/second; held until the zero-crossing of the roll rate signal signifies maximum roll angle; then is ramped at 600 degrees/second to -180 degrees steer; and is held there for at least 3 seconds. This maneuver is sufficiently severe to cause tip-up at 0.83g lateral acceleration in older Trackers, and one-wheel lift but not tip-up in the 2001 model. Tire shoulder wear rate is very severe at the left front, but light at the left rear unless the vehicle repeatedly spins out. At the right front wear is very light, and at the right rear it is non-existent, because these tires are unloaded or off the ground during the protracted part of the maneuver.

TEST VARIABLES

Factors which affect the test data are the temperature of tire and pavement, the uniformity of the test surface, the pause in steer before reversal at max roll angle, the break-in "looseness" and viscoelastic "memory" of the tire carcass, and the tread shoulder wear. Of these, only the pavement could not be studied, since the vehicle speed, but not location on the test surface, was controlled.

TIRE MEASUREMENTS

During each test run the usual vehicle state variables were measured: speed, steer, throttle, brakes, yaw velocity, roll velocity, roll angle, roll-stabilized lateral and fore accelerations. In addition, the lateral sidewall deformation of the right front tire was measured with an ultrasonic device. Immediately after each run the shoulder tread temperature and the shoulder wear were measured manually. The principal data sought were the variation in peak sidewall deformation vs run number; shoulder wear vs run number; and lateral acceleration vs shoulder wear and run number.

SIDEWALL DEFORMATION MEASUREMENT

A "Migatron" ultrasonic detector was installed on a bracket attached to the ball stud of the lower ball joint, as shown in Figure 5, looking at the tire sidewall. As it thus became "part of the steering knuckle", its measurements were independent of suspension or steering motions.

SHOULDER WEAR MEASUREMENT

The device for shoulder wear measurement is shown in Figures 6 (with the left front tire mounted on the spare "for show"), and in Figure 7. A mounting plate was attached to extensions of the wheel lugnuts. After each test run an articulated arm was located on this plate by dowel pins and locked in place by a spring-loaded 1/4 turn knob. Then the dial indicator was slipped into the articulated arm and a reading taken.

TREAD TEMPERATURE

Immediately after each run, before the shoulder wear measurement, a hand-held, eighth-inch diameter thermocouple probe with digital readout was forced against a shoulder groove until the observed temperature stabilized. This reading was recorded verbally on the test videotape, along with the shoulder wear measurement.

TIRE BREAK-IN

The tires were unused prior to the test. Warm-up consisted of driving back and forth over the test area with a 1 Hz, 60 degree sinusoidal steer (about 0.3g peak), followed by driving on a circle at 0.3 g for one minute in each direction.

TIRE VISCOELASTICITY

A tire is a viscoelastic system having both short-term and long-term memory. A tire which experiences carcass stress returns approximately to the unstressed state with a time constant of about 15 minutes; and more fully after several days[3]. To compensate for this behavior, runs 4 thru 16 were run at precise 7 minute intervals, so that the viscoelastic decay would be uniform. The first three runs were 4 minutes apart to see if they differed. There was a one-half hour break between runs 16 and 17, again to determine whether it made a significant difference.

STEER PAUSE

Steer reversal occurs when the roll rate enters a "window" around zero, at maximum roll angle. However, for some vehicles (the Tracker is the worst case seen so far) there is a "hump" in the roll rate near the zero-crossing, as hown in Figure 8. If the roll rate enters the window before the hump the pause is short: if it enters the window after the hump it is longer. Sensitivity to steer pause length is plotted in this report. The cause of the hump has not been determined. The recorded data in Volume 2 includes suspension rate and tire deflection, for analysis of their individual contributions to roll rate in a separate report.

TEST RESULTS

DATA PLOTS

Each data plot shows a least-squares regression line along with two types of limits: the 95 percent confidence interval with dashed lines; and the 95 percent prediction interval with solid lines. The confidence interval includes the “true” regression line with 95 percent probability. And, for any given value of the independent variable, with 95 percent probability a measurement of the dependent variable will lie within the prediction interval. Both first-order and second-order regression lines are plotted , since in some cases the second-order appears to make a better fit, with reduced standard deviations.

When the confidence interval includes a horizontal line: i.e., a constant value for the dependent variable, it is reasonable to claim that within the limits of the experiment the dependent variable is not significantly affected by the independent variable.

SHOULDER WEAR vs RUN NUMBER

The rate of shoulder wear is plotted in Figures 9 and 10. The wear resulting from the 19 test runs was about .075 inches, or nearly 2 millimeters. Figure 11 is a detail of the right front tire shoulder and sidewall wear after 19 runs. For the 10 runs used in a typical ATI rollover threshold search the wear was about about 46 thousandths, or a bit over 1 millimeter.

LATERAL ACCELERATION vs RUN NUMBER AND SHOULDER WEAR

The test data of Figures 12 and 13 show no increase or decrease in lateral acceleration with run number. Similarly, Figures 13 and 14 show no increase or decrease with shoulder wear.

TIRE DEFORMATION vs RUN NUMBER

The test data of Figures 15 and 16 show a an increase of 3.3 percent over the first 10 runs, and 6.6 percent over the 19 test runs. Since the tire deformation of 2.4 inches is approximately 10 percent of the half-trackwidth, the change represents a decrease in T/2h of approximately 0.3 percent in a typical 10-run threshold search..

TREAD TEMPERATURE vs RUN NUMBER

Tire tread temperature increased by 19 degrees during the test, due to insufficient warmup (Figure 17). This mistake caused a question regarding the degree to which the tire's lateral deformation and lateral acceleration were due to temperature or shoulder wear.

LATERAL ACCELERATION vs TEMPERATURE

Lateral acceleration plotted against tread temperature in Figures 18 and 19 show no significant effect over this fairly narrow temperature range. Also, since temperature is measured after the run and cooling occurs during the time between runs, it cannot be known whether temperature causes or is caused by lateral acceleration. This question will be addressed in a future program in which tread temperature and the tire's internal temperature and pressure are measured continuously through a slip ring assembly.

LATERAL ACCELERATION vs STEER PAUSE

Figures 20 and 21 indicate the effect of steer pause. Pause variation is a factor which can be and will be improved.

CONCLUSIONS AND COMMENTS

Based on the limited testing in this study, tire shoulder wear is no longer a confounding problem in “using repetitive runs as a means of searching for the limit”. When the limit has been identified by a systematic search program, a “definitive” determination can be made with “virgin” tires, if desired.

The test program described herein utilized only a “highway” tire. For completeness, it will be repeated with a tire having a more aggressive “All-Terrain” tread design.

We expect that the variation in steer pause caused by the hump in roll rate feedback can be reduced by a combination of high-frequency noise filtering and low-frequency proportional-plus derivative signal shaping..

TABULATED DATA

RUN	TIME	TEMP deg.F	WEAR mils	DELAY Sec.	DEFL. in.	Ay g's	COMMENTS
0-AM		75.9	8				Before first AM run
1	1-15:29	80.4	6	.319	2.455	.825	
2	1-19:38	82.8	14	.289	2.490	.829	
3	1-22:45	86.7	15	.289	2.535	.827	
4	1-26:40	89.1	20	.326	2.455	.825	
5	1-33:42	88.4	34	.326	2.383	.849	
6	1-40:41	85.8	38	.381	2.510	.830	
7	1-47:40	89.4	43	.314	2.490	.846	
8	1-54:34	87.6	47	.303	2.525	.838	
9	2-01:50	91.7	51	.406	2.455	.816	
10	2-08:49	89.5	49	.317	2.485	.822	
11	2-15:49	93.6	59	.289	2.640	.845	
12	2-22:46	94.8	60	.271	2.565	.838	
13	2-29:44	90.3	62	.271	2.605	.834	
14	2-36:44	92.0	67	.319	2.560	.833	
15	2-43:42	92.8	65	.353	2.480	.809	
16	2-47:29	91.2	70	.321	2.610	.838	Break for 1/2 hour.
							Circular path warmup
0-PM		89.5	70				Before first PM run
17	2-50:33	89.5	75	.321	2.650	.844	
18		89.5	75				Recorder off, no data
19	2-56:05	91.5	85	.315	2.525	.825	

Tire deflection and lateral acceleration readings had a 0.5 second running-average filter.
Tire peak lateral deflection: Average 2.523; Standard deviation 0.072
Peak lateral acceleration: Average 0.832g; standard deviation 0.011

Steer delay before reversal: Average 0.318; standard deviation 0.035

RECORDED DATA

CHANNEL	ITEM	FULL SCALE	MODULE
1	Vehicle speed	100 mph	Speed
2	Steer	1000 deg.	1B
3	Throttle	100 percent	1A
4	Brakes	1000 pounds	2B
5	Yaw Rate	100 deg/sec	3A
6	Roll Rate	100 deg/sec	3B
7	Ay	1 g	4A
8	Gyro Roll angle	20 degrees	5B
9	Outrigger	1000 pounds	2A
10	Suspension Rate RF	100 inches/second	8B
11	Tire defl. RF Vert	10 inches	7A
12	Tire defl. LF Horiz	10 inches	7B

ATMOSPHERE

Pavement:	60 degrees, 48.7 percent relative humidity
Air:	55 degrees, 55 percent relative humidity

VEHICLE LOADING

Instrumentation was installed on an 18-pound pressed-wood panel replacing the front passenger seat. Instrumentation consisted of Sprint 3 Steering Machine Electronics Box at 11 pounds, Data System at 14 pounds, Humphrey stabilized accelerometer platform at 38 pounds, Video tape recorder at 1 pound, and electrical power junction box at 1 pound on the passenger-seat panel; and a *Sprint 3* battery/electronics box (used as battery box only) at 32 pounds. *Sprint 1* Steering Machine at 22 pounds was mounted on the vehicle steering wheel. The interior video camera (3 pounds with mounting post) was mounted immediately behind the front seats. The fifth wheel mounting bracket at 2 pounds was mounted on the rear trailer hitch, and the trailing fifth wheel weighed 14 pounds. The total instrument system weighed 174 pounds. The removed front seat weighed 30 pounds, so the net gain was 144 pounds with its CG at 31.2 inches. The instrumentation installation is shown in Figures 1-4.

The driver weight was 265 pounds at a CG height of approximately 36 inches.

The fuel tank was full before each day's testing, to prevent slosh effects.

WHEEL WEIGHTS AS TESTED, WITH DRIVER

Left Front	866
Right Front	788
Left Rear	822
Right Rear	792
Total	3268
Percent front	50.6
Percent left	51.6

PROGRAMMABLE STEERING MACHINE

The Heitz *Sprint 1* Programmable Steering was used to generate accurate and repeatable steer inputs at precise test speeds. In operation the program inputs a 600 degrees/second ramp to a fixed change from the initial straight-ahead steer; holds that steer until the roll rate approaches zero, indicating that max roll angle is achieved; then ramps at 600 degrees/second through a second steer angle change, and after 3 seconds returns slowly to zero. The *Sprint 1* and *Sprint 2* machines require the machine, an Electronics Box, and a Battery Box. The *Sprint 3* combines the Electronics and Battery boxes into one unit which is smaller, more rugged, and with a more reliable battery charging system. For this test the *Sprint 3* "B/E Box" was installed, but only the battery section was used.

TEST AREA

The test area is level with a gradient less than one percent. The surface is "New Jersey FABC Interagency 5" blacktop, which is designed for public highways. Measurement of the macrotexture in the test area according to ASTM E965-1996 showed a mean texture depth of 0.95 mm, which is typical of blacktop highways (e.g., I-295 near Bordentown NJ measures 0.90 mm). The friction coefficient has not yet been measured, but from same-vehicle testing it is believed to be about 0.03g lower than the Vehicle Dynamics Area at Transportation Research Center in Ohio.

ATMOSPHERIC CONDITIONS

In the tip-up area the pavement temperature was 60 degrees with relative humidity 48.7 percent. The air temperature at the roadside camera was 55 degrees with relative humidity 55 percent.

TRANSDUCERS USED

Speed and distance: ATI-developed all-weather fifth wheel with a 45 pulses/foot optical encoder sealed inside the hub. Distance output 10 or 1 pulse/ft by BCD rate multiplier, calibrated to ±1 ft. over a taped 1877 ft. distance. Speed obtained thru frequency-to-voltage converter, with crystal calibration to 100 mph full-scale.

Steer Angle: Heitz *Sprint 1* steering machine.

Throttle position: Tap into vehicle throttle pot.

Brake effort: LEBOW 3363-200 brake pedal load cell. 200 pounds full-scale; linearity 0.1 percent. Cal by precision TROEMER NBS Class F weights.

X,Y,Z accelerations, pitch, roll, yaw velocities: HUMPHREY INERTIAL MEASUREMENT UNIT. Roll angle erection accuracy 0.15 degrees. Erection rate 1 degree/minute. Contains X, Y, Z, linear accelerometers, SUNDSTRAND Model 303: Full scale 1 g, linearity 0.05 percent. Contains roll, pitch, and yaw rate gyroscopes, in NORTHRUP Nortronics 3-axis DC-DC rate gyro package, S/N 17. 90 deg/sec FS; linearity 0.5 percent; threshold 0.01 deg/sec. Accelerometer calibration by tilting 90 degrees; rate gyro calibration on 36 degree/second rate table.

Thermocouple probe: OMEGA Model P01J221K4FQ with digital readout OMEGA Model HH501BK.

Tire Deflections: MIGATRON Model RPS-401A. Analog output 0-10 volts, zero & span adjustable. Full-scale span 5 to 30 inches, minimum distance 5 inches, maximum distance 40 inches. Operating frequency 212 kHz. Accuracy ±0.040 inches or ±0.3 percent, whichever is greater.

DATA ACQUISITION SYSTEM

All data is conditioned in instrumentation amplifiers, and anti-alias-filtered in tenth-order 14.2 hz Butterworth active filters. The filters use precision operational amplifiers, one-percent resistors, and temperature-stable capacitors matched to .1 percent. The filter characteristic is flat to one part in 4000 at 10 hz and is down 66 db at 30 hz. The filtered data is sampled 60 times per second, digitized to 12 bit accuracy and resolution, and stored on one horizontal line of a video recorder. The data line appears as a dot-dash line across the top of the visible video picture.

The video camera is mounted next to the driver's head, giving a driver's eye view of the vehicle interior, steering wheel, and roadway ahead. Driver commentary, engine and tire noise, etc., are recorded on the video recorder sound track.

The digitized data is shown as an overlay on the video picture as a vertical array of numerics, each ranging from -1000 to +1000 full scale. The numeric display is updated 60 times per second, on every video field, for single-framing analysis. In running the test, numerics are shown on a video monitor for a visual check of proper transducer operation.

Only the data line must be recorded, as the other displays can be regenerated during playback, or recorded on the picture during editing.

The system also has a plug-in "RAM Buffer" module, which serves as an interface to an IBM - PC computer. Thru this module, the computer sees the data being reproduced as RAM which is updated with twelve 12-bit data samples in a 53 microsecond burst occurring sixty times per second. Various "handshake" lines and data flags are provided for easy software access.

DELAY IN STEER REVERSAL AFTER MAX ROLL ANGLE

Reversal of steer is triggered by zero crossing of <u>filtered</u> roll rate.

Delay in filter is 0.067 seconds.
Delay in servo circuitry is 0.014 seconds.
Total delay is 0.081 seconds.

INSTRUMENT LOCATIONS

Item	**Weight pounds**	**Height inches**	**Moment inch-pounds**
Original seat	-30	27.3	-819
Front-seat panel	18	26.3	473
Humphrey	38	30.3	1151
Data system	14	31.3	438
Electronics Box	11	31.3	344
Steering Machine	22	39.0	858
Video tape recorder	1	35.8	36
Video camera and monopod	3	45.0	135
Junction box	1	27.3	27
Fifth wheel	14	12.0	168
Fifth wheel bumper bracket	2	18.0	36
Rear seat panel	18	31.3	563
Battery box	32	33.8	1082
Totals	**144**	**31.2**	**4492**
Driver	265	36.0	

OUTRIGGER WEIGHTS

Item	**Weight pounds**	**Height inches**	**Moment inch-pounds**
Roof rail brackets	2x7	65	1170
Roof cross tube	7	69	552
Lower control arms	2x14	10	420
Strut, Driver side	11	41	553
Strut, Passenger side	7	40	480
Underbody structure	16	10.5	346
Totals	**83**	**31**	**3522**

LIST OF FIGURES

REFERENCES

1. RD Ervin, PS Fancher, L Segal, *Refinement and Application of Open-Loop Limit-Maneuver response Methods*, SAE Paper 730941.
2. *Specifications for ATI Rollover Test Protocols*, http://www.atiheitz.com/rolltest.pdf
3. K.D.Marshall, R.L.Phelps, M.G.Pottinger, and W.Pelz, *The Effect of Tire Break-In on Force and Moment Properties*, SAE Paper 770870.

Figure 1: Exterior view of vehicle as tested

Figure 2: Exterior view of vehicle as tested

Figure 3: Steering Machine, Machine Command Module, Stable platform caging & erection switches.

Figure 4: Steering Machine in foreground; Stable Platform with VTR atop (center), Data Acquisition system (rear) in background.

Figure 5: Ultrasonic transducer for tire lateral deflection.

Figure 6: Tire shoulder wear measuring assembly (Right front tire after test).

Figure 7: Right front tire with dial indicator after Run #18.

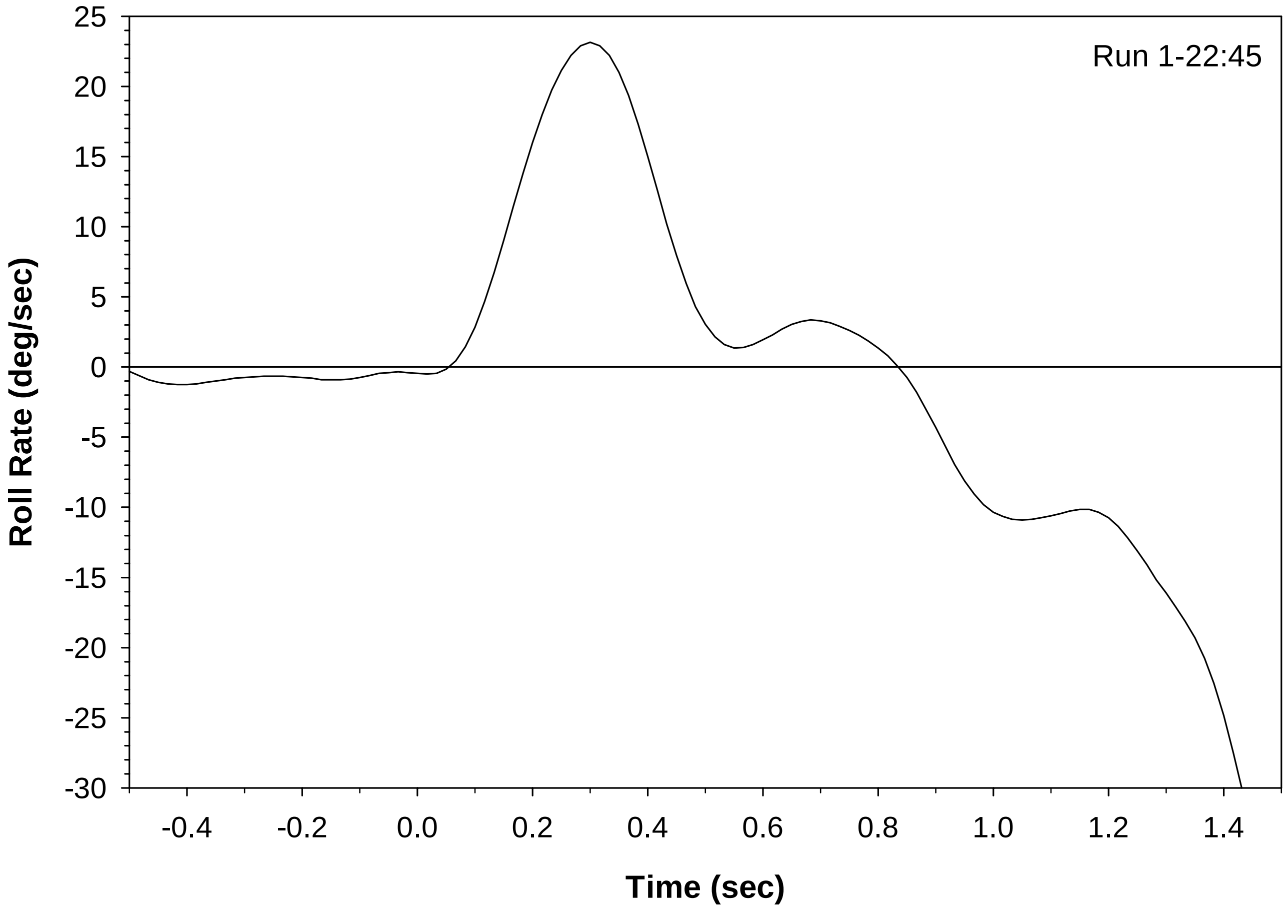

Figure 8: Typical roll rate showing “hump” near zero-crossing.

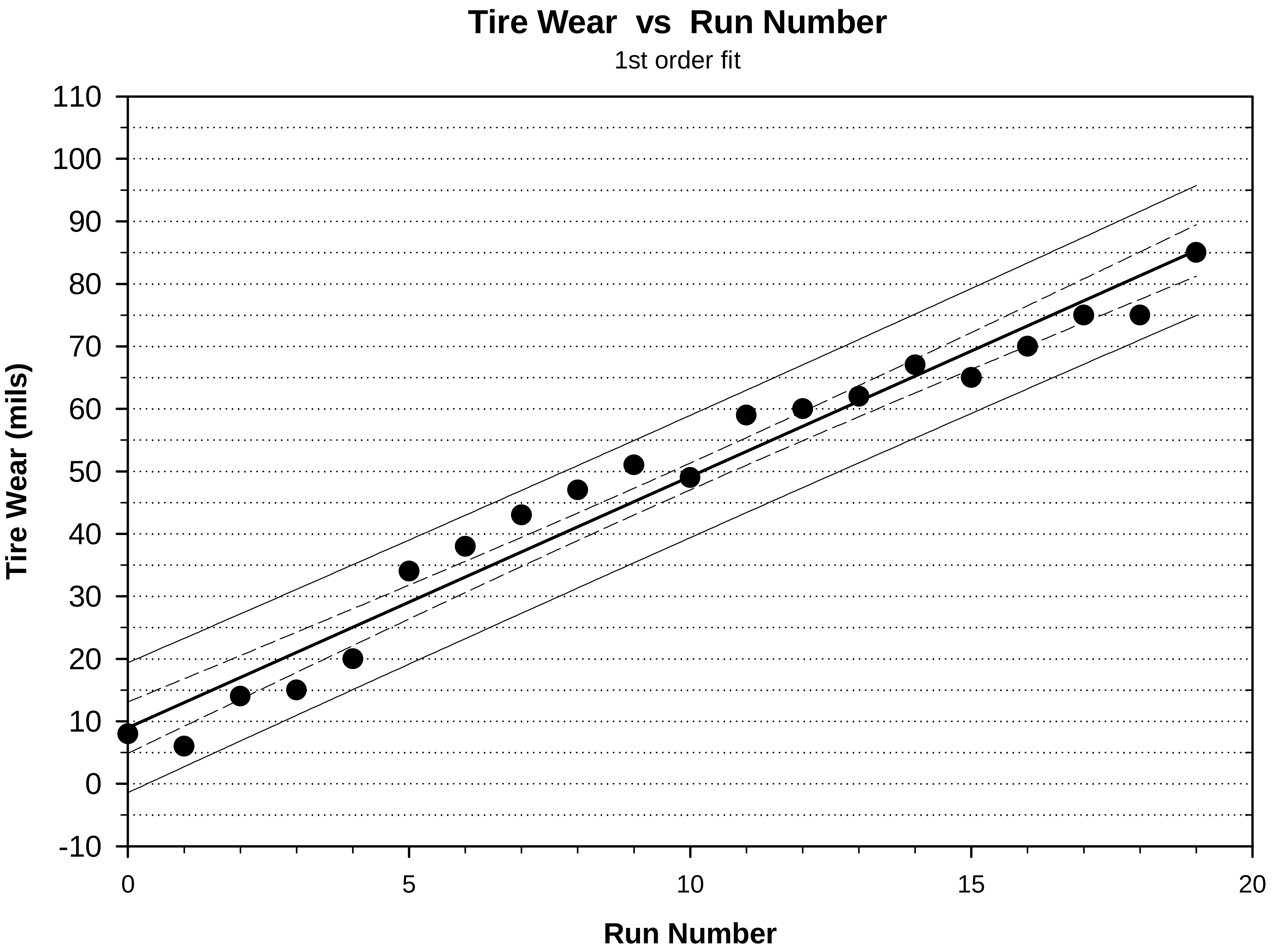

Figure 9: Tire shoulder wear vs run number, first order fit.

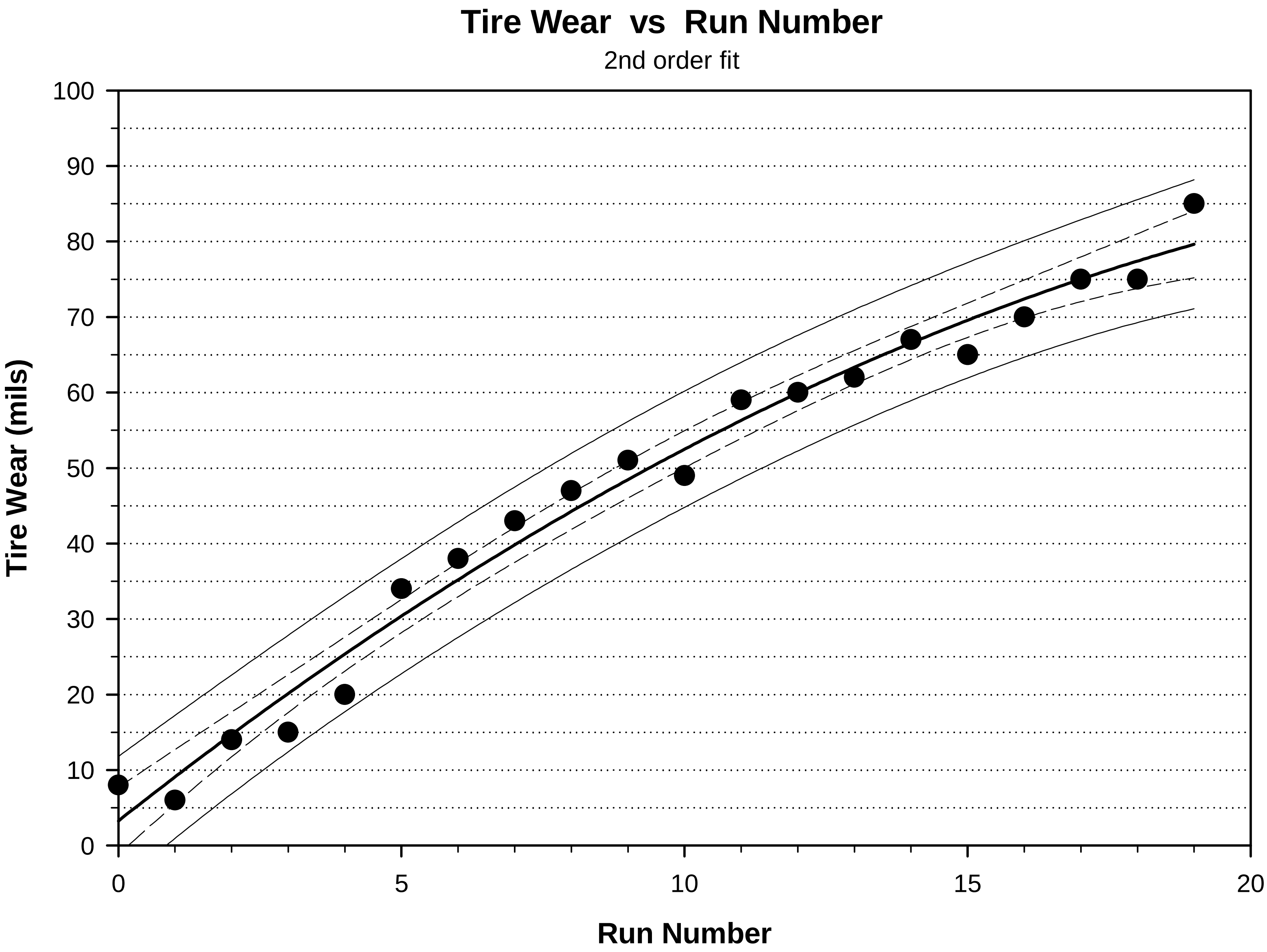

Figure 10: Tire shoulder wear vs run number, second order fit.

Figure 11: Detail of right front tire shoulder after test.

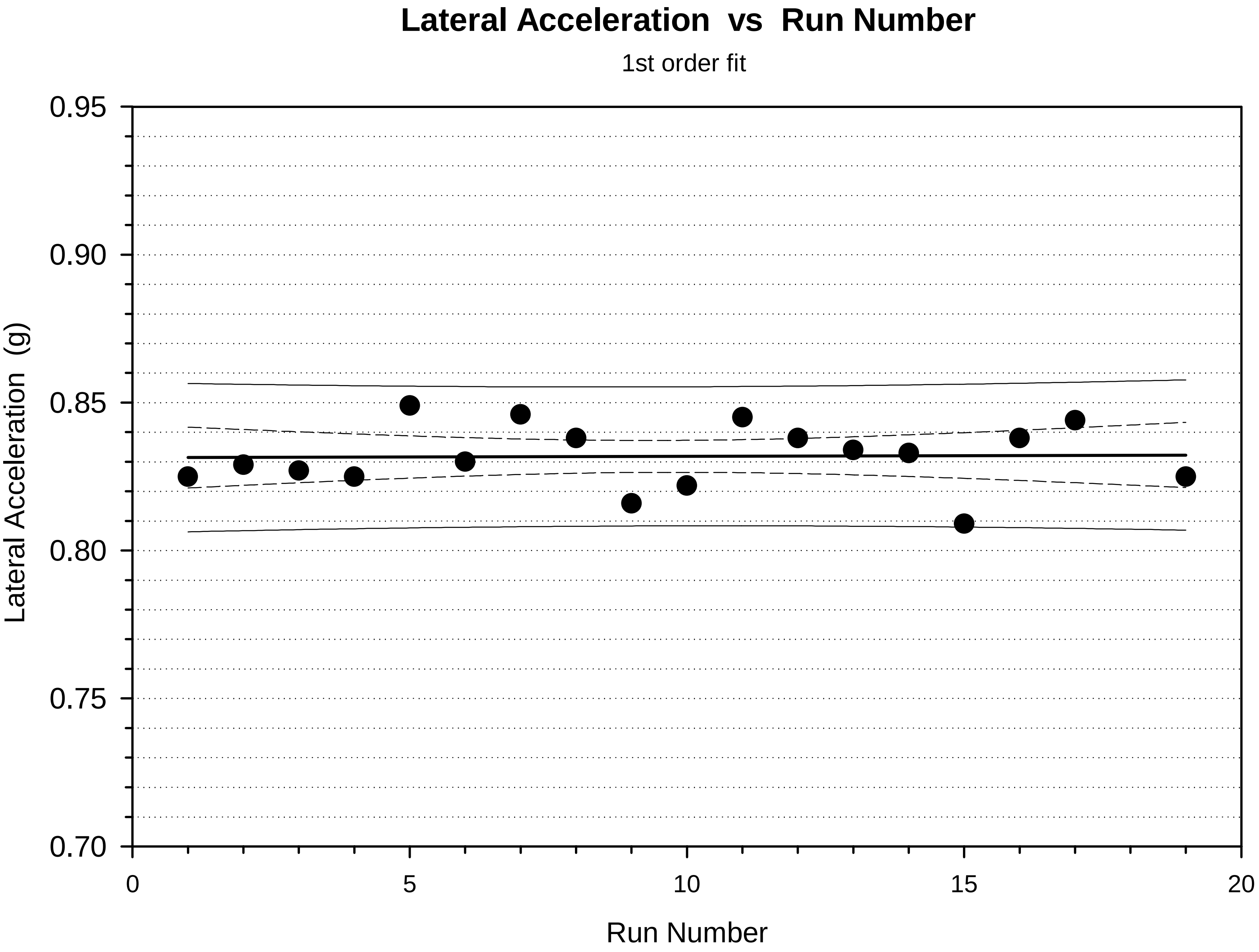

Figure 12: Lateral acceleration vs run number, first order fit.

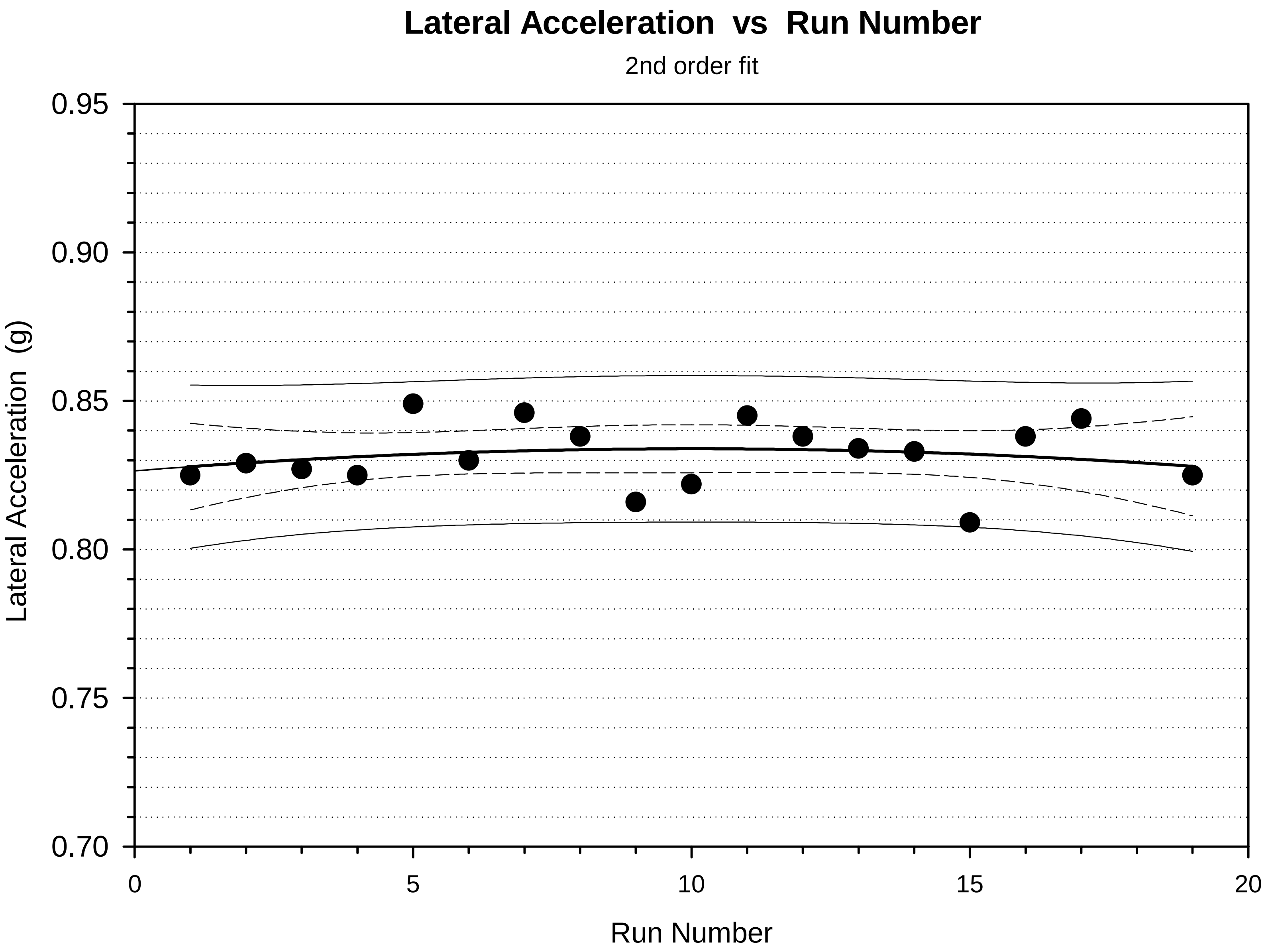

Figure 13: Lateral acceleration vs run number, second order fit.

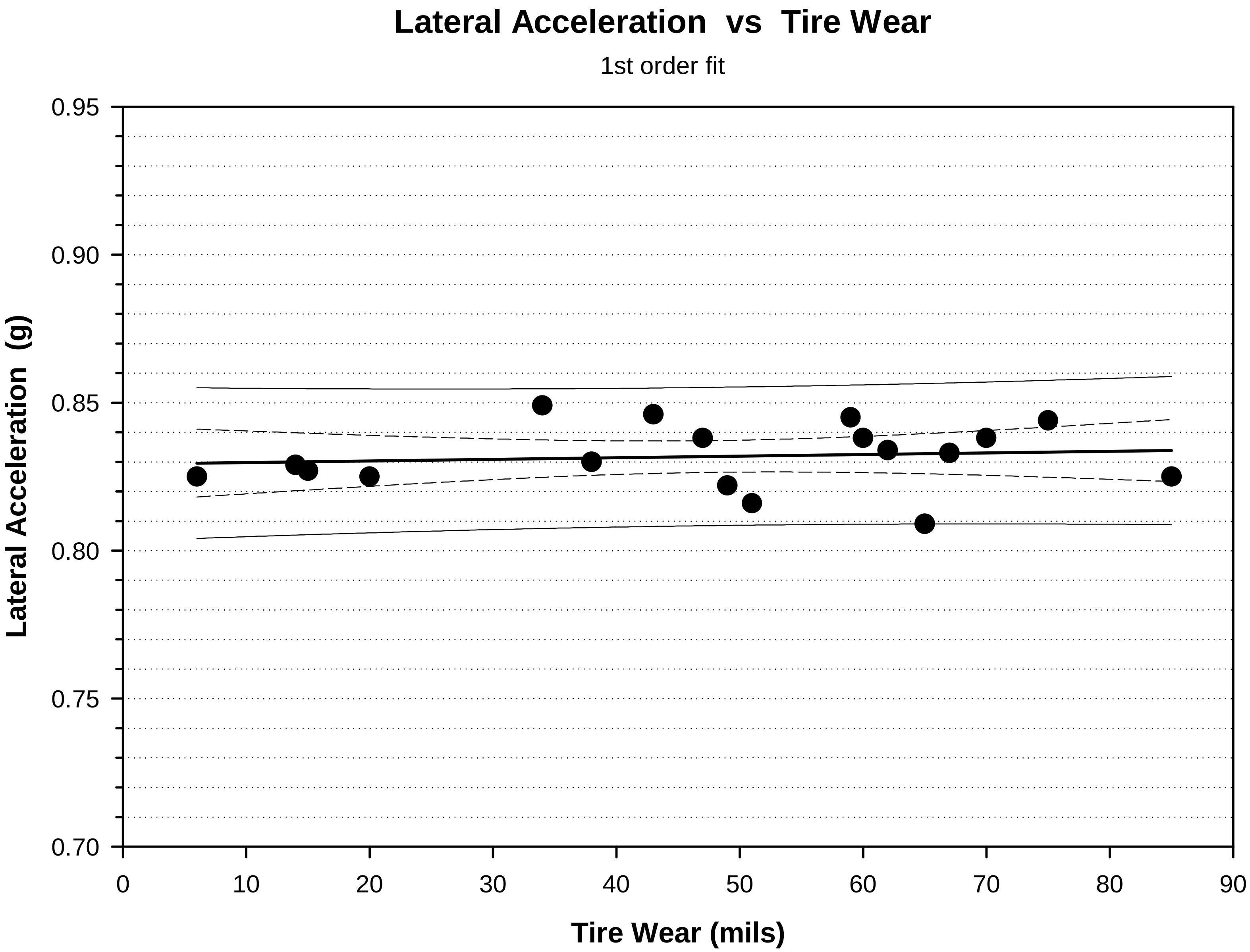

Figure 14: Lateral acceleration vs shoulder wear, first order fit.

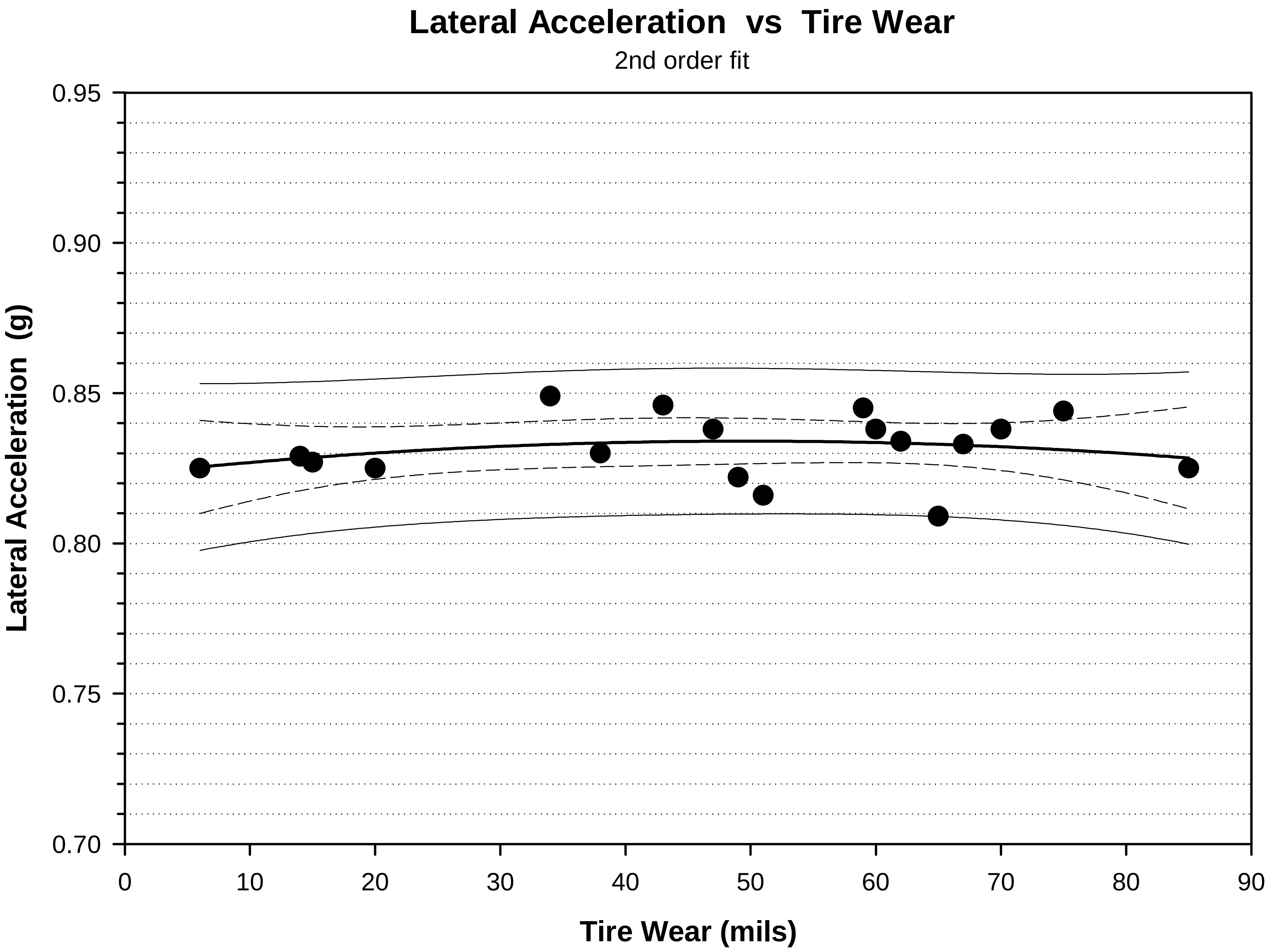

Figure 15: Lateral acceleration vs shoulder wear, second order fit.

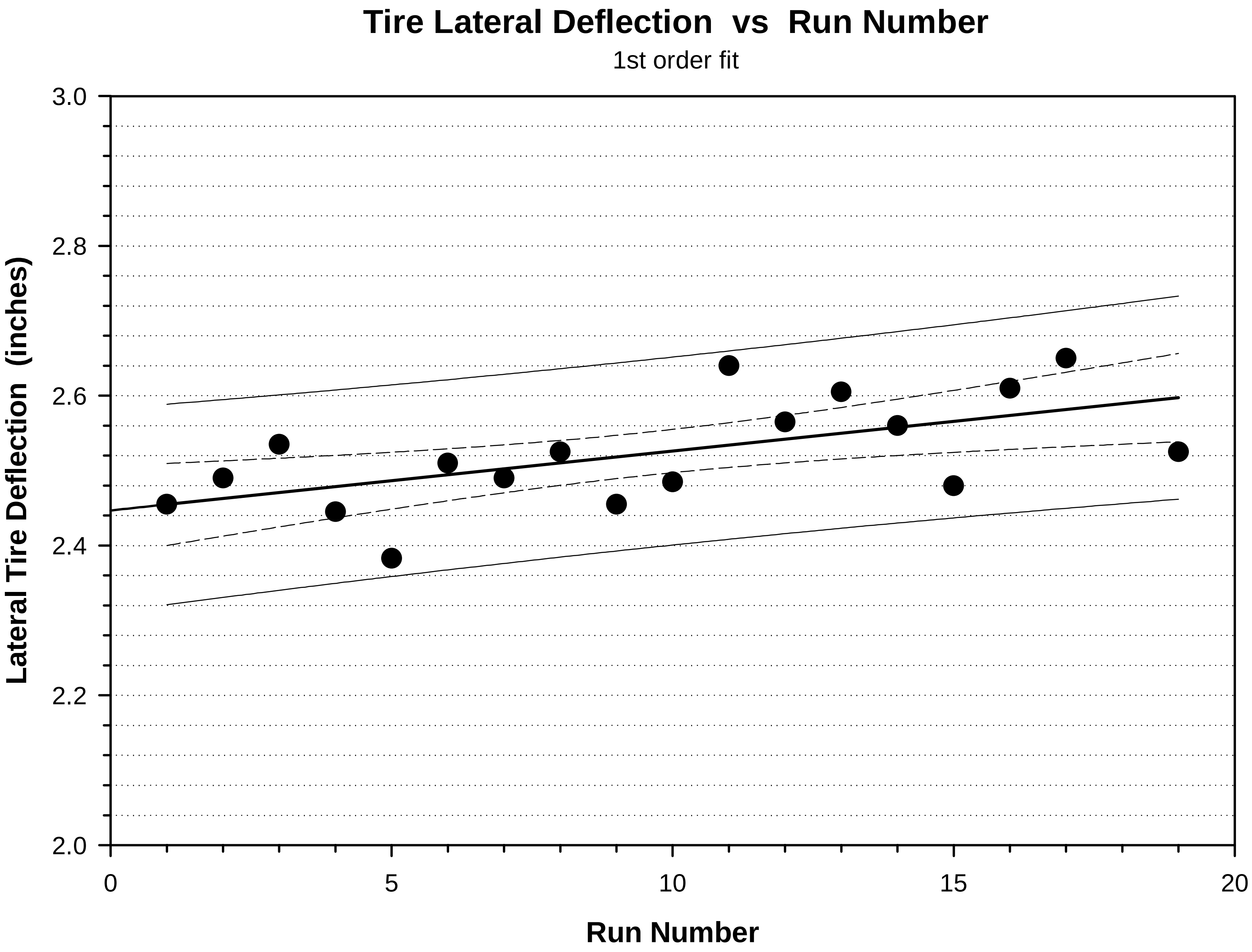

Figure 16: Tire lateral deflection vs run number, first order fit.

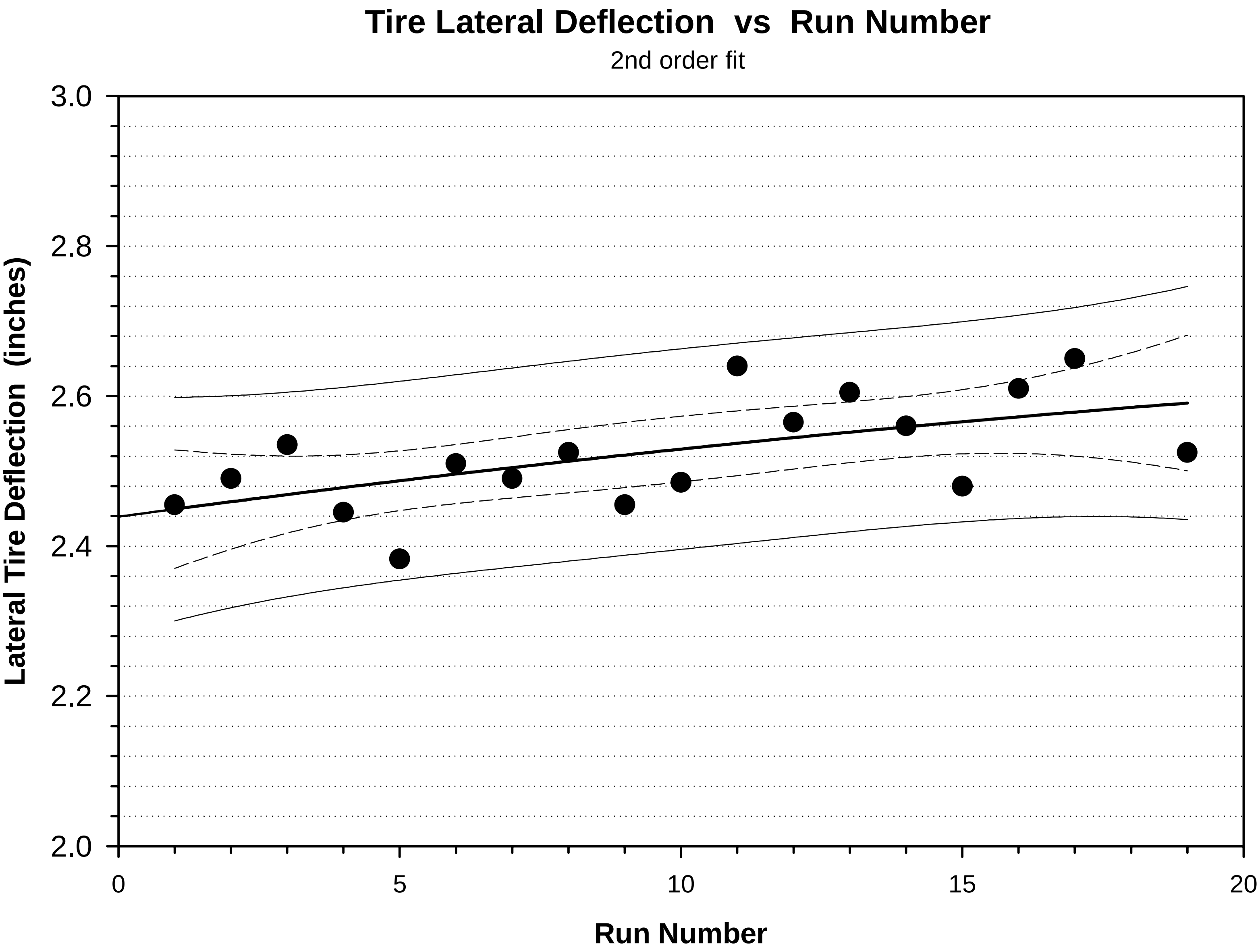

Figure 17: Tire lateral deflection vs run number, second order fit.

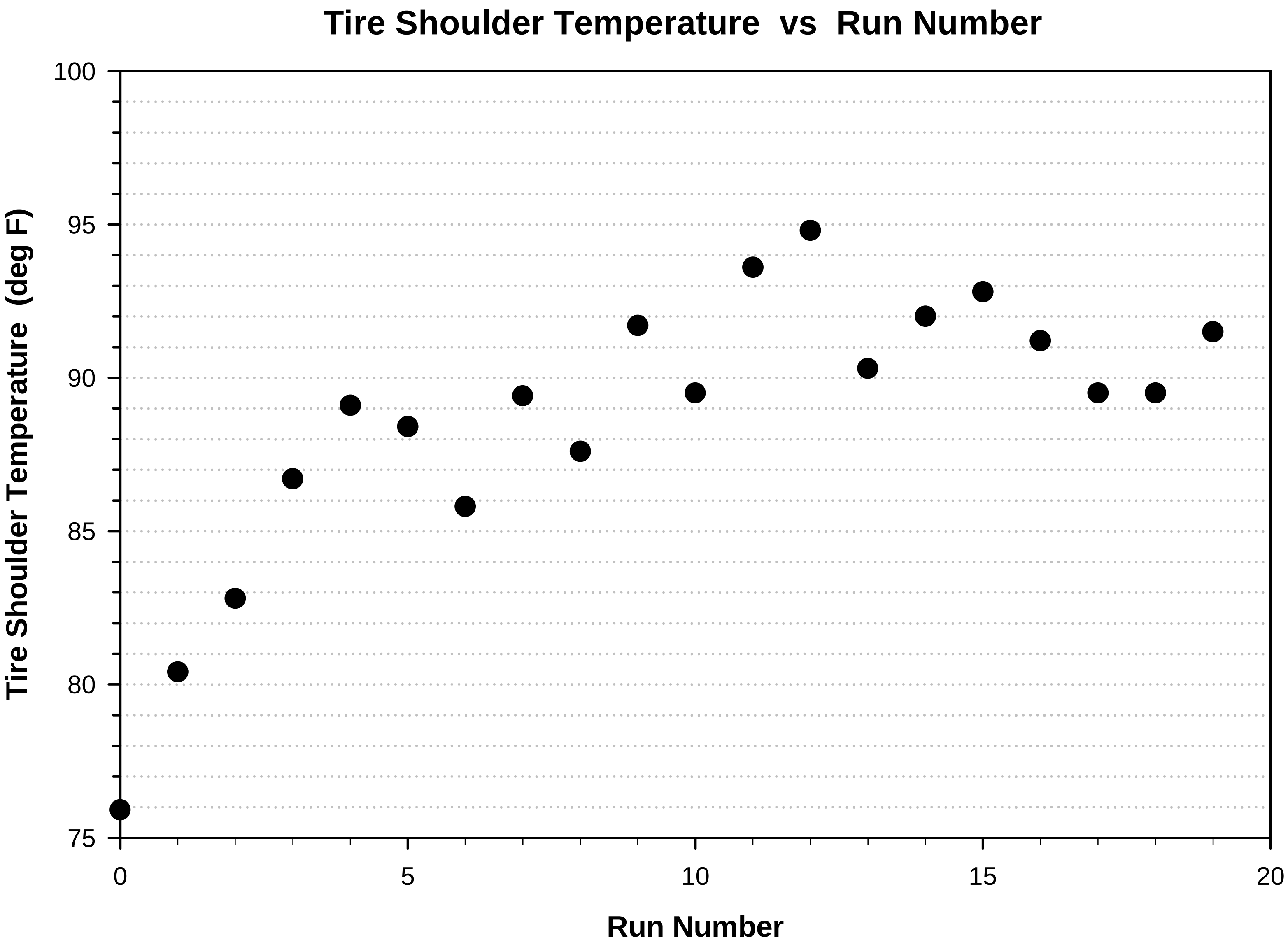

Figure 18: Tire shoulder temperature vs run number.

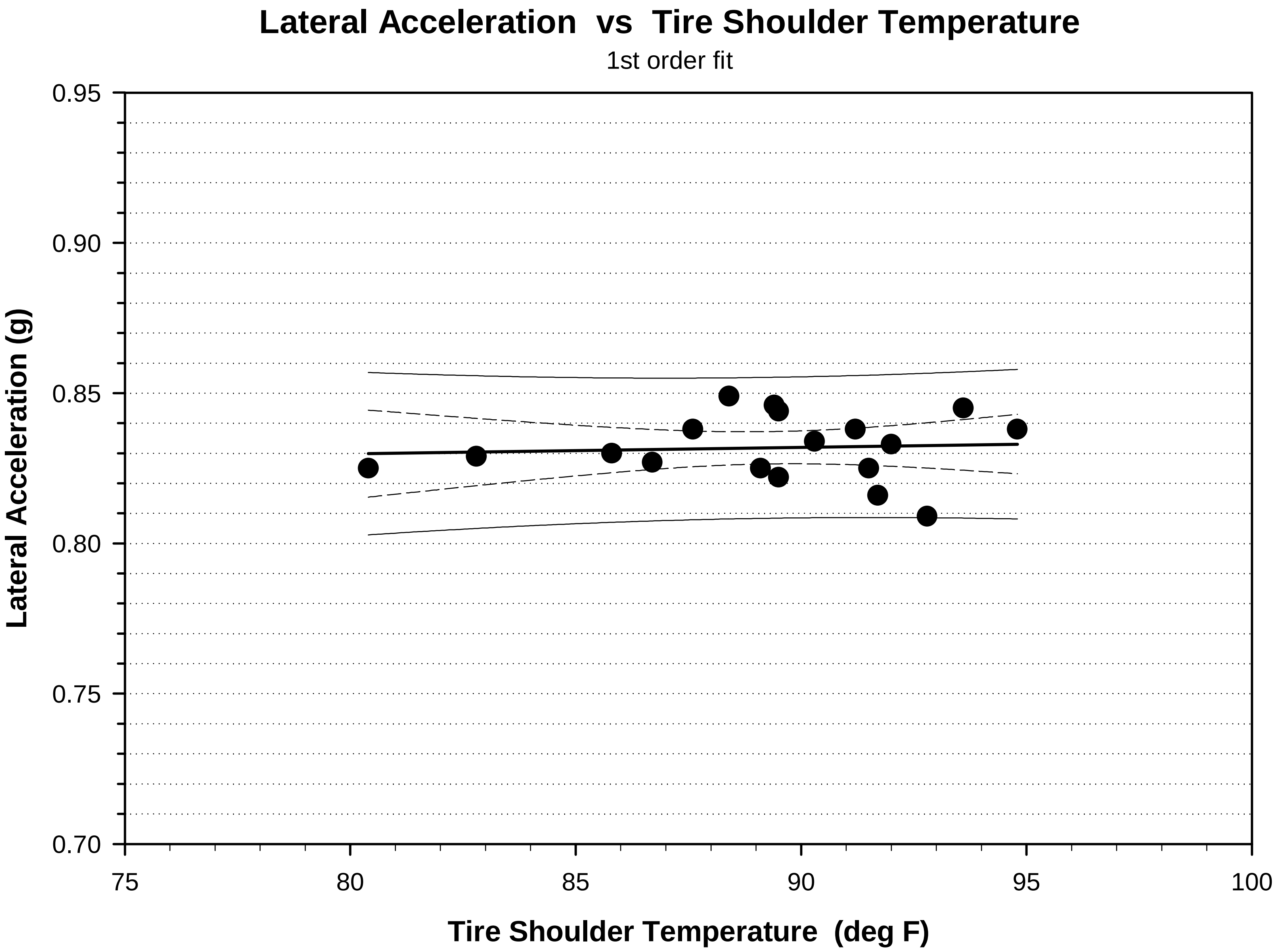

Figure 19: Lateral acceleration vs tire shoulder temperature, first order fit.

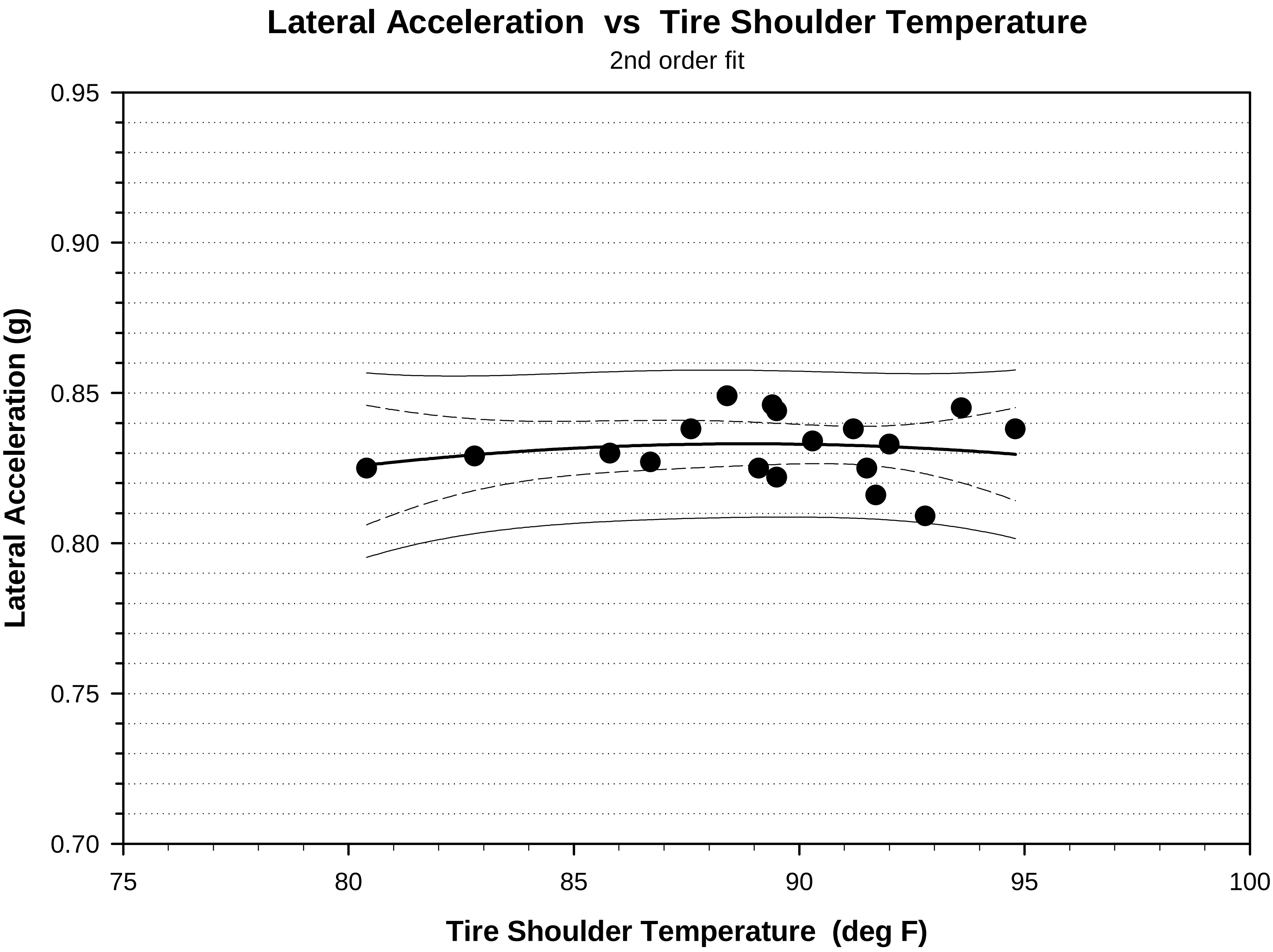

Figure 20: Lateral acceleration vs tire shoulder temperature, second order fit.

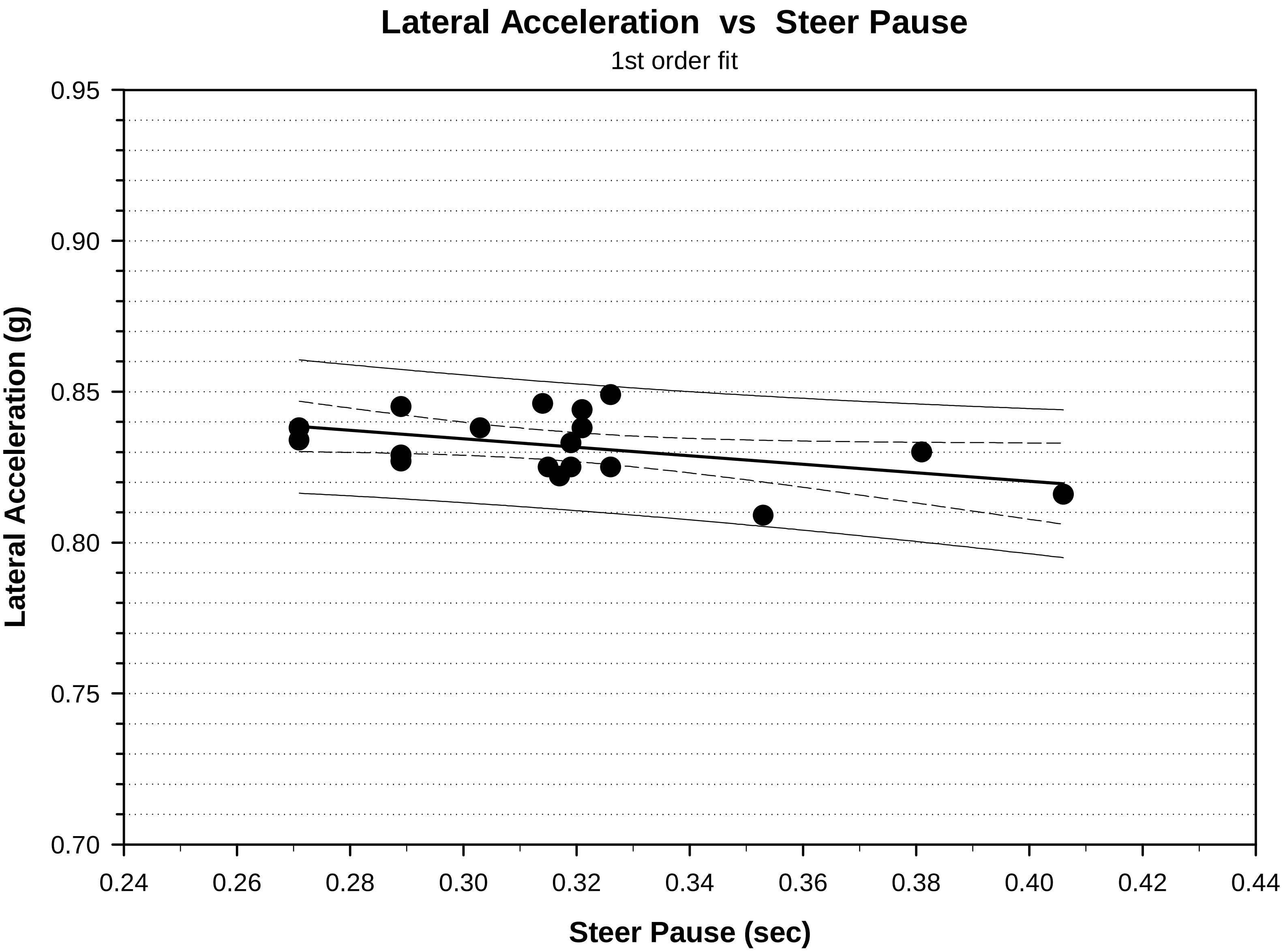

Figure 21: Lateral acceleration vs steer pause, first order fit.

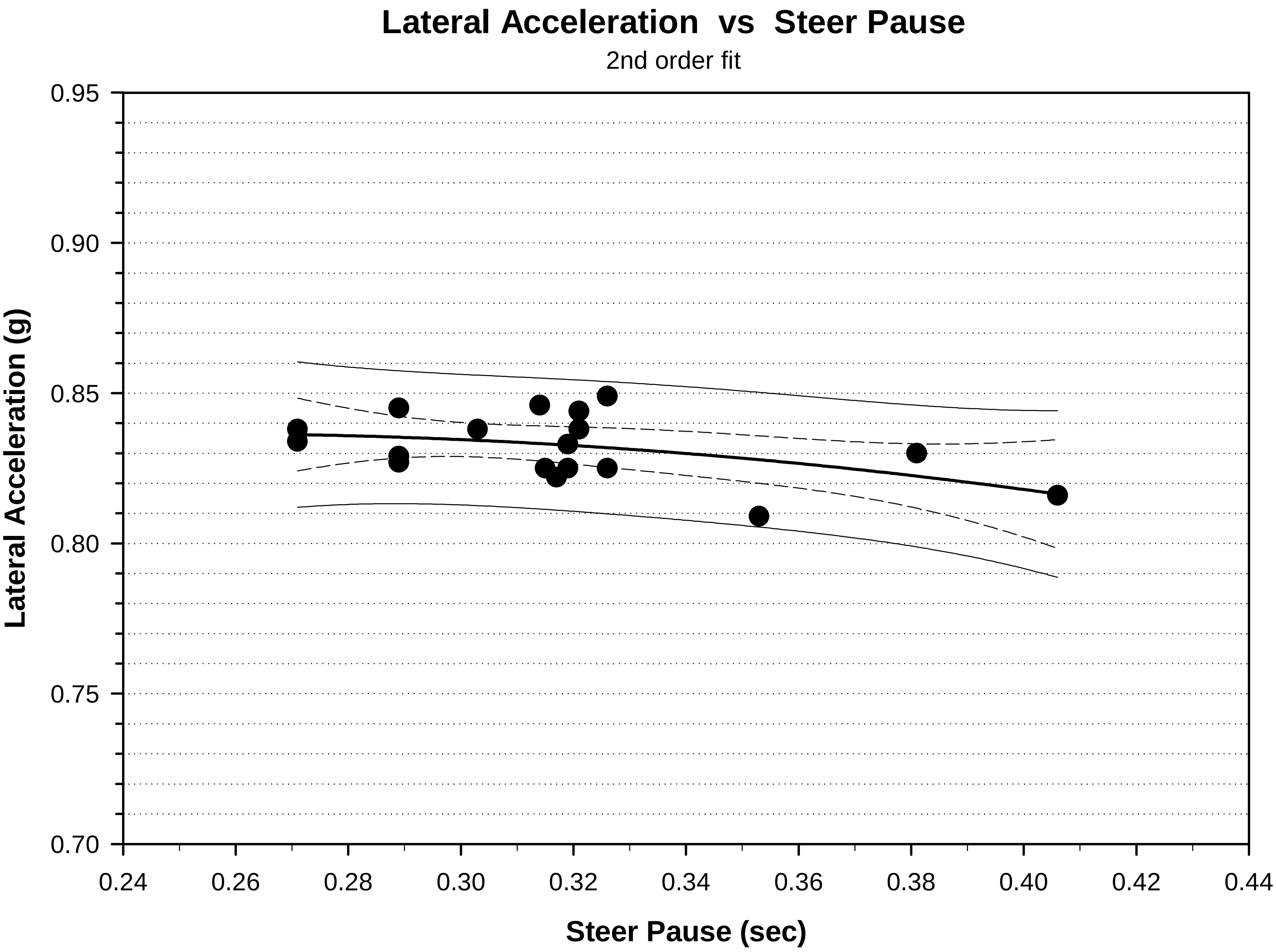

Figure 22: Lateral acceleration vs steer pause, second order fit.