Making Sense of Squiggly Lines

the
Basic Analysis
of
Race Car Data Acquisition

written by:
Christopher Brown

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Nomenclature used throughout the book includes:

△ *Warning*: Denotes a warning to help the reader avoid potential pitfalls.

Note: Signals key notes to remember.

☑ Check: Tells the reader to check something in their data system.

Acknowledgements

Taking on the challenge of writing a book is equal to embarking on a journey into the unknown. Only after finishing does one know the true cost in terms of time required to complete the journey. For all those who stood beside me during this time, thank you.

The knowledge base that I gathered for writing this book started from my childhood experiences in motorsport, thanks in part to my parents whom never stifled my interests. From building CO_2 dragsters in middle school to racing radio-controlled cars in high school. The next level of higher education left me knowing just enough to be dangerous. But even so, my life at Oregon State University helped build a solid foundation for which I now stand on.

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Preface

I've often wondered why there weren't more books available on data acquisition for racing. Perhaps those that know how to do it wish to keep their intellectual property to themselves? Or perhaps the market for such a book is too small? I've been told there is no money to be made in writing a book about racing, only some notoriety and perhaps an ego boost. For me, this book was written to fill a void in the knowledge base of race car data acquisition.

Race car data acquisition is a complicated topic, and experience in doing it is the best way to learn it. Most people just stumble along getting less than half of the total information available in their data. Worse are those that get tricked into the many pitfalls of data, making wrong conclusions and then ignoring the data because it seemed wrong.

This book is about analyzing data acquisition for driver analysis. It is not about how to use your data acquisition software, setup your data logger, or what changes to make to your race car. Those are subjects for another book……

Open to learning, resistant to frustration.

People with a computer background will be able to learn their analysis software very quickly. Those with a background in racing will be able to relate their experiences into what they see. A bit of both makes the perfect combination.

Crap in equals crap out.

The number of pitfalls in data analysis are endless. Crappy or incomplete data will make your job seem impossible and lead you to the wrong conclusions.

The more sensors on the car, the more time it will take to analyze them.

There is little point to putting more sensors on the car if you don't have time to analyze them. Especially when the driver is also the engineer.

Data adds to a driver's feedback. It does not replace it.

Like a detective, the engineer is to solve the case of how to make the race car go faster. Logged data provides the clues, and the driver is the sole witness. Experience teaches us which clues to examine first and how to relate to the driver. Never make a conclusion without seeing all the evidence.

90% of being fast is from the driver. 10% is from the car.

The first goal of data acquisition is to improve the driver. Only with a professional driver at the controls will there be more gained by adjusting the car than the driver. A true professional can extract 90% of the car's speed with almost any setup on the car. The information used for tuning the car will often require more advanced sensors. And that's a subject for another book……

↳ *Note:* Some drivers cannot be adjusted.

Chapter 1 Introduction

Data is any type of information about a subject. It could be words, numbers, graphical, audio or video. All of which apply directly to the subject of racing cars. *Acquisition* is a term meaning "to acquire". Therefore *data acquisition* denotes "to acquire information". Analysis is the process of interpreting our acquired data, most commonly for the goal of making the race car or driver faster.

In racing the first data logger was simply a stopwatch, pen and paper. When more advanced systems first appeared in racing they were not completely digital loggers. They were strip chart recorders which drew traces of information onto a continuous roll of paper. The paper was laid out onto clear tables that featured bright lights underneath. The lights shined up through the paper, allowing two sheets from different laps to lay on top of one another. Similar to examining an X-ray with a bright light behind it. These devices also transmitted the data for real time telemetry to the pits and across phone lines to engineering offices, mostly located back in Detroit.

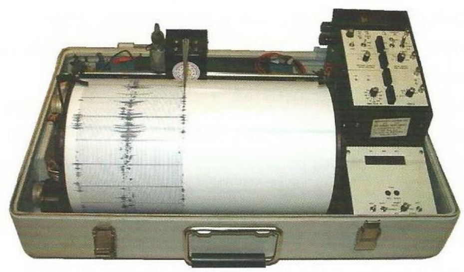


Figure 1.1 *Similar to a seismograph, data systems used in racing in the 1960's measured and recorded information with a pen and paper.*

Today data loggers not only record information digitally, they perform many other necessary functions in a race car. The data system displays information for the driver, notification of alarms, and activate lights to help the driver time their gear shifts. Newer data systems integrate video recorders that keep a synchronized playback with the data. Video is not only limited to recording what the driver sees out the windshield or the line they drive, but also for viewing aero tufts, suspension movement and tire sidewall deflection. Recording infrared video for temperature mapping of a tire is also possible now.

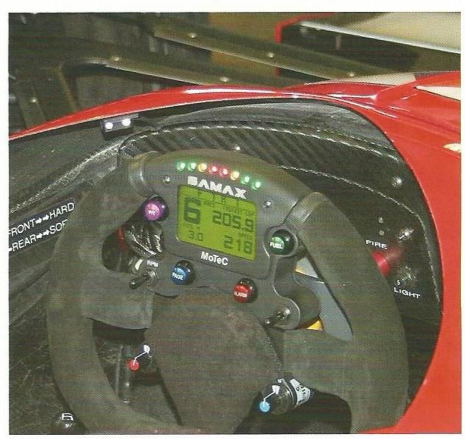


Figure 1.2 *Display and shift lights mounted directly into a steering wheel.*

1.1 Data Acquisition System

A data acquisition system is comprised of many components. The main component is the data logger itself. Various sensors are connected to the logger so their measurement can be recorded. The recorded data is then downloaded through a cable into a computer and viewed with special software to help analyze it. Many other functions are also performed by the logger such as a display and shift lights to help the driver know when to shift.

There are so many things to consider when selecting a data system, an entire book could be written on that topic alone. There are many manufacturers of data acquisition systems and choosing one can be daunting. Each one is unique and varies in style, features and capabilities. Some units can only accept a few sensors while others can record over 100 sensors. The sensors are mostly common and therefore interchangeable between any data system. But the recorded data files are not interchangeable with other data systems. Rather each manufacturer has their own unique analysis software. So when selecting a system, check to see what other racers are using if you wish to compare their data to yours.

Figure 1.3 *Overview of the data acquisition system.*

Data Logger & Displays

The data logger might feature a built into display as shown above in ***Figure 1.3***. Or it could have a separate display for the driver such as the steering wheel on the prior page in ***Figure 1.2***. This type of display requires a separate data logger box located elsewhere in the car.

Figure 1.4 *Logger only box.*

Sensor

The sensor converts a measurement of some physical property, like temperature, pressure, distance, speed, force, etc. into a corresponding electrical signal. This electrical signal will vary to represent the measurement through either amplitude (varying voltage levels) or by frequency (rate of on/off pulses). The signal is sent into the data system through the wiring harness where it is converted into digital bits and recorded. The analysis software converts these digital bits of information back into the measured value.

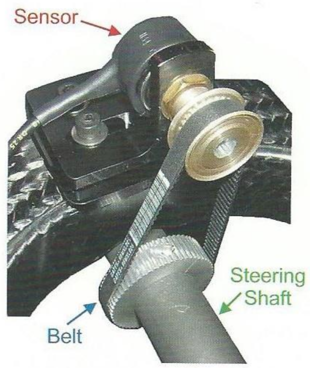


Figure 1.5 *For measuring steering angle, a rotary position sensor measures the steering shaft rotation through a toothed belt.*

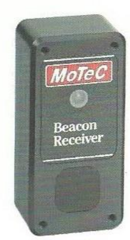
Figure 1.6 *Three axis accelerometer.*

Wiring Harness

The wiring harness runs throughout the race car, much like a set of blood vessels do inside our bodies. They provide power to each sensor and carries back the electrical signal to the data logger where each signal gets recorded. The wiring harness might consist of a homemade collection of wires and electrical connectors costing a couple hundred dollars, or it can be professional made with aerospace quality connectors for a couple thousand dollars.

Figure 1.7 *A wiring harness used to connect sensors to the logger.*

Beacon



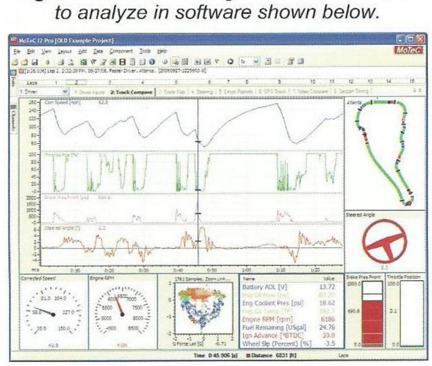
An essential part of every data system is the lap beacon. Alongside the track sits a beacon transmitter that sends out pulsed infrared light which a human eye cannot see. Inside the race car is a lap beacon receiver which sees this light and triggers the start of a lap. It functions to provide lap times to the driver and to accurately locate the start of every lap. When comparing multiple laps during analysis, it's imperative that each lap have the exact same start location. The infrared beacon can produce laps within 0.001 seconds of accuracy.

Instead of an infrared beacon, some low cost data systems utilize GPS locations to trigger the start of each lap. Accuracy is based on both the update rate and precision of the GPS data. Some GPS units can only update at 5 Hz (one data point every 0.200 seconds) and therefore must interpolate between two data points to find the actual start/finish line. Typical accuracy with GPS beacons is around 0.020 seconds. But the ease and cost make GPS based beacons very attractive.

Download

The process of transferring the logged data into the laptop is called downloading. It usually happens with a cable connected directly from the data logger to a laptop. For fear of two-way data communication while the car is on the race track, sanctioning bodies who oversee the rules commonly outlaw wireless downloading.

Figure 1.8 *Downloading data after a session to analyze in software shown below.*



Analysis Software

The real heart of a data system is not necessarily the logger hardware inside the car, but the software used for analysis on the laptop. You'll spend the most amount of time in front of this computer program, so it goes without saying that having the best analysis software is important. Get one that is easy to use, doesn't crash or cause problems, and has the functions you need. Each manufacturer will have their own unique software, and the data files will not be interchangeable to other data systems.

Track / Circuit / Venue

Depending on what side of the large pond you live, there are different names for what all means the same thing. A track, circuit or venue is the name of the location you're racing at. In the United States, the word track is used most often while in England the word circuit is more frequently used.

Session / Outing / Run

Each time a race car goes out onto the track for some period of time, it can be called either a *session*, *outing* or *run*. The words *practice* or *test* might refer to a single session or to the entire day made up of multiple sessions.

Telemetry

Telemetry might be the name of a street, but that's not what you will find in a dictionary. Telemetry means to gather data from a distance. So sending live data from the car into the pits would be considered *telemetry data*. The data which is logged on the car and then downloaded into the laptop through a cable is not telemetry data. This would be called *logged data* because it is not gathered from afar.

In some classes of motorsport, sanctioning bodies allow one way communication from the race car to the pits. This telemetry is helpful to the pit crews and engineers so they can keep an eye on everything that is happening with the race car. It allows the driver to concentrate on driving without worries of their car's health. Telemetry aids in safety by allowing teams to monitor things like engine oil pressure, tire pressure and bearing temperature. Any problems with one of those on a high speed track could send the car straight into a wall without any warning or notice to the driver.

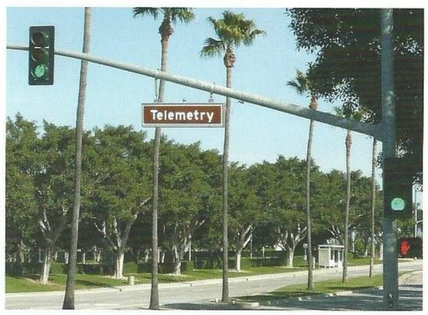


Figure 1.9 *Some terms used in racing have different meanings outside of the racing world.*

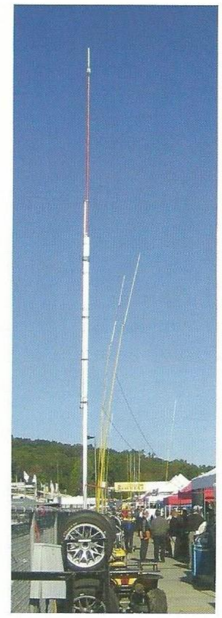


Figure 1.10 *Long antenna masts are used along pit lane.*

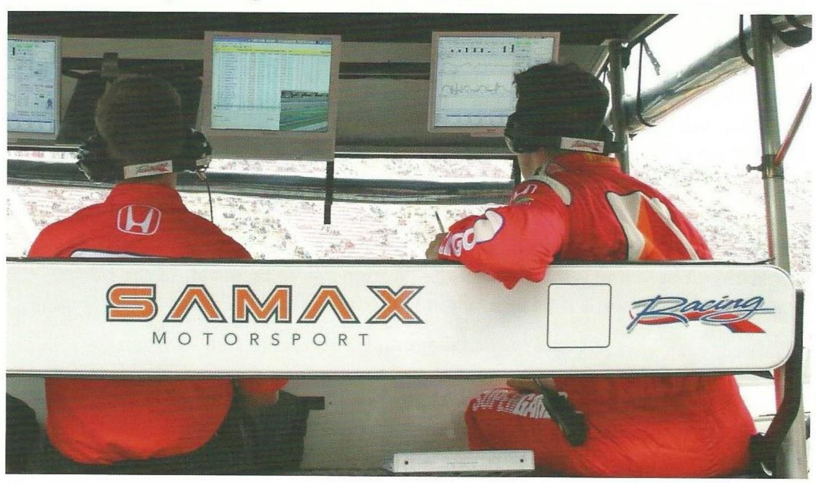


Figure 1.11 *Data streams from the car to the team's row of monitors in pit lane.*

1.2 Channels

Each channel is a parameter of information on the race car that gets measured and then recorded. Similar to a television, data systems include many different channels to watch. One such channel is the speed of the car. Another is the steering wheel angle. The six basic channels that all data systems should include are listed below. These six will form the basis of this book. The more channels of information, the more clear an engineer and driver can be about what is happening on the race track.

The six basic channels

- speed
- RPM
- throttle
- g-force lateral
- g-force longitudinal
- steering

Advanced chassis channels

- brake switch (on/off)
- brake pressure
- brake rotor temp
- brake pad wear
- g-force vertical
- damper / shock movement
- ride height
- tire / suspension load
- tire pressure
- tire temp
- air speed
- angular rate for yaw, roll & pitch
- anti-roll bar setting

Engine channels

- engine temp (water)
- oil temp
- oil pressure
- fuel temp
- fuel pressure
- fuel mixture or lambda
- exhaust temp
- air temp
- manifold pressure
- barometric pressure
- crankcase pressure

System channels

- battery voltage
- coolant pressure
- clutch pressure
- fuel used / remaining
- gear
- gearbox temp
- gearbox oil pressure
- gear shift force
- cockpit temp

This book is going to concentrate on analyzing data for driver development. The six basic channels will provide plenty of information for that. Little time will be spent analyzing engine channels other than RPM. But since all of those engine channels are important to the health of the engine, they should not be ignored. Data acquisition can also be used to create detailed engine run logs which are important for the engine builder and the crew who maintains the engines. Data can also be used to track mileage on each gear inside the gearbox or any other part on the car. Professional teams have mileage limits on every part of a race car. Those parts get changed out for new ones, before they break!

The 6 Basic Channels

Speed

The measurement of how fast the race car is going. Depending on which side of the large pond you live, the most common unit for speed is either mph (miles per hour) or km/h (kilometers per hour). The scientific community calls this velocity rather than speed, and uses a unit of m/s (meters per second). Most analysis programs can easily convert between different units depending on what you prefer.

Engine RPM

As the name states, Engine RPM is rotations per minute or speed of the engine. The scientific measuring unit is Hz (hertz) or rotations per second. But everyone has adopted rotations per minute as the common unit. The speed of the engine is directly related to the speed of the car, through different ratios in the gearbox which transfers engine rotations into wheel rotations.

Throttle

How far the driver presses down on the gas pedal is called throttle or throttle position. This could be measured as a length of pedal travel or rotational angle of the throttle blade. To make this easier to understand, it is best to calibrate this channel as a percentage of full throttle instead of pedal travel or blade angle. A throttle position of 50% will therefore equate to half of the full measurement. It could mean the gas pedal is pressed half way down by the driver, or the throttle blade angle is half open. Either way, the percentage allows for easier comparisons between different cars.

Note: A throttle position of 50% does not equate to 50% of engine power! Power output from the engine does not follow a linear relationship to throttle. It is dependant on the pedal geometry and throttle blade movement. In newer cars it depends on the programming of the drive-by-wire system.

G Force Lat & Long

These channels don't measure a force, rather they measure accelerations of the race car. To make a lot of the math easier, these accelerations are normalized to the Earth's gravitational pull. The unit is G and one G is equal to an acceleration of 9.81 m/sec^2. Acceleration when combined with a subject's mass creates a force. For example, if you weigh 150 lbs and are turning a corner in your race car with 2 G's of force, then your body is pushing against the seat with 300 lbs of force.

Steering

How far the steering wheel is rotated will be measured in degrees and called steering wheel angle. A full circle is 360 degrees and therefore a quarter turn is 90 degrees. Some cars will measure steered angle instead, which is the angle of the tires and not the steering wheel.

Order to the Corners

For a top level team where hundredths of a second are important, relentless amounts of time and effort are spent analyzing data. Data analysis becomes an engineering exercise and the law of diminishing returns begins to kick in. To be effective and quick at analyzing data a certain amount of organization is needed. So we will start with some typical conventions chosen to keep things simple.

Obvious to many is the front and rear of the car, but what about left and right? For this we take the reference of the driver sitting in the car. Left for the car is left for the driver. When facing an oncoming car, the car's right is your left and the car's left is your right.

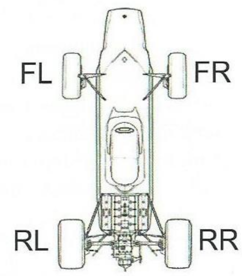


Figure 1.12 *Abbreviations for road race vehicles.*

There are two conventions for abbreviations. The preferred method is FL for front left, FR for front right, RL for rear left and RR for rear right. To aid in reading squiggly lines it is recommended to graph no more than two traces in the same group. For road racing it makes sense to graph the fronts separately from the rears. As FL, FR, RL, RR is alphabetical, the fronts should be graphed above the rears as one might expect.

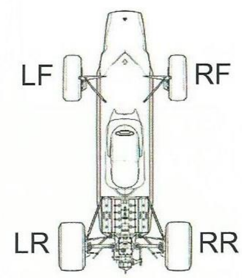


Figure 1.13 *Abbreviations for oval only vehicles.*

Oval racers often choose the other convention of LF, LR, RF, RR. This makes more sense for them because the differences between the left and right sides of the vehicle is greater than the differences between the front and rear. The left channels are graphed together and are above the right channels.

When it comes to G forces acting on the car, G Force Lat, G Force Long and G Force Vert should also be listed and graphed in alphabetical order.

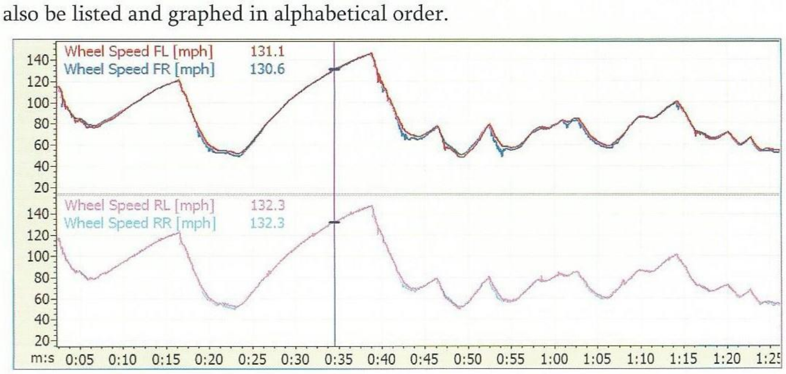


Figure 1.14 *When displaying channels that are unique to each corner of the car like individual wheel speeds, it is a common practice to place the fronts on top and in alphabetical order.*

Channel Colors

There is no standardization of colors used in data acquisition. Teams pick their own colors, but the most important thing is to remain consistent. Having unique colors for each channel can help identify traces much quicker than having to read its label. This book recommends the following colors, which were picked based on experience of shuffling through data over many years.

When choosing a color for those channels that exist on each corner, such as wheel speeds, shock movement or tire pressures, try to maintain the same color scheme for any corner based channels. When graphed, it becomes second nature to know that red channels are left and blue channels are right. See ***Figure 1.14*** for a graph of the four individual wheel speed channels.

The channel colors used throughout this book will be:

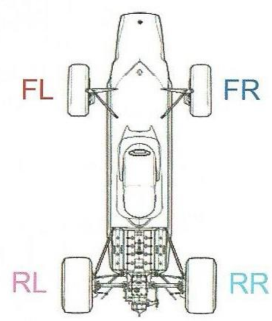


Figure 1.15 *Colors for each side of the car should be similar, with different shades front to rear.*

Speed
RPM
Throttle
Steering
G-Force Lat
G-Force Long
Gear

System Colors

For the purpose of printing this book, the background color of all graphs will be white. However, for most people it will be easier to see graphs when using a black background. This is due to a larger contrast difference between the colored lines and the background. Light colors can be more easily distinguished on a black background than dark colors on a white background. Because smaller variations in color can be identified, a black background provides a larger pallet of colors to select from.

One of the most important things to consider when shopping for a laptop to be used for data acquisition, is the readability of the screen outside when sunlight is present. While some glossy screens look bright, their glare and direct sunlight performance is often worse than matte screens. In either case, a black background behind the data will help.

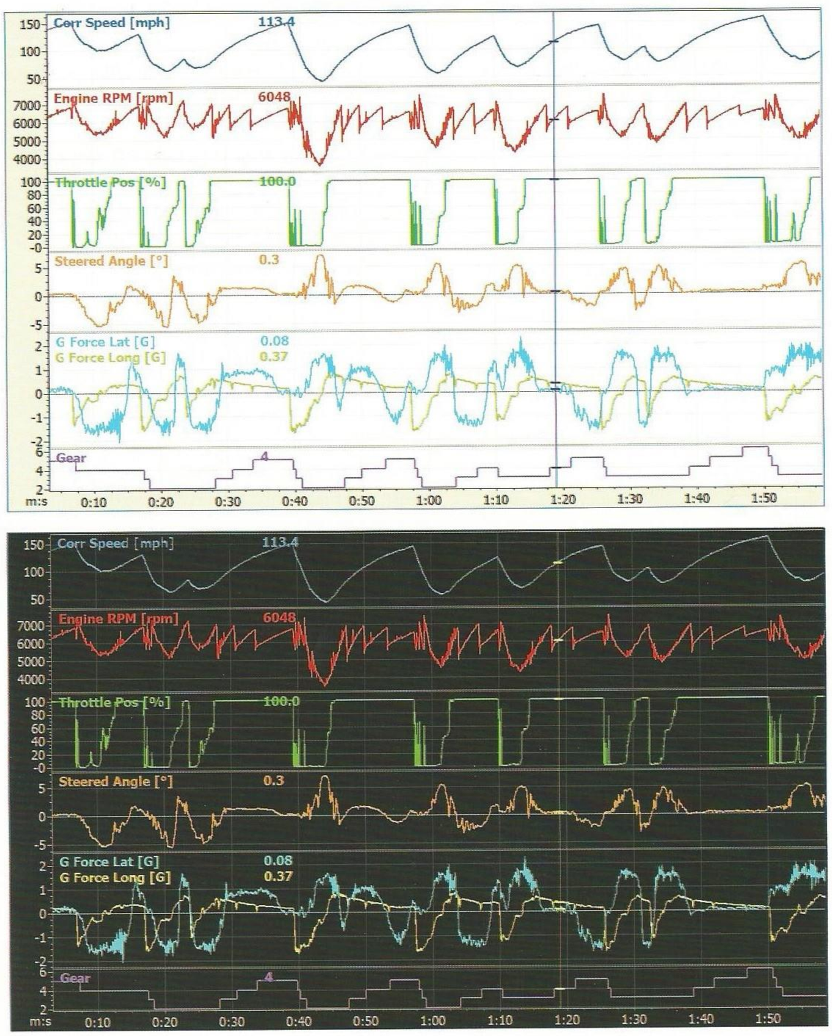


Figure 1.16 *All the colors above are identical on both graphs. Notice how most colors stand out more with a black background? They tend to be more discernable with the black background.*

1.3 Logging

The action of recording is called *logging*. Channels of data from multiple sensors are logged into memory of the data system. The data system does not log graphs or curves. Rather it logs individual data values at specific moments in time. These individual data values or data points, are connected with straight lines to form the digitized recording of the sensor. This process is called digitization of an analog signal, much like the digital recording of a music CD.

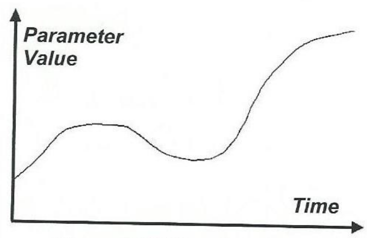


Figure 1.17 *The original curve created from the measurement of a sensor over a given time period.*

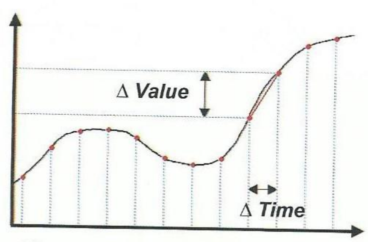


Figure 1.18 *Single points of data are logged at specific time intervals.*

Table 1.1 *Parameter values as recorded in the logger for the graphs of speed on this page:*

Time (seconds)	Speed (mph)	Engine (rpm)
0:38.10	108	6300
0:38.20	118	6990
0:38.30	122	8020
0:38.40	123	8100
0:38.50	120	7800
0:38.60	115	6750
0:38.70	114	6720
0:38.80	115	6750
0:38.90	125	8400
0:39.00	137	9010

The first step is to take the sensor measurement of the physical parameter (speed, rpm, etc.) and record its value at a constant rate or time interval. The value changes as each data point is taken at a different moment in time.

The change in sensor value divided by the change in time, creates a slope in the line connecting two points. The slope is a measure of steepness in the curve. See the red line connecting two red dots in ***Figure 1.18***. Areas with little change in the sensor value over time are flat. Areas with large changes are steep.

These data points are logged into memory at a fixed time interval. The terms *logging* and *sampling* are interchangeable. See ***Table 1.1*** for an example of how this data looks in the logger.

After downloading the logged data, these data points are plotted with lines connecting each one. The goal being to reconstruct the original curve from measurements the sensor reported.

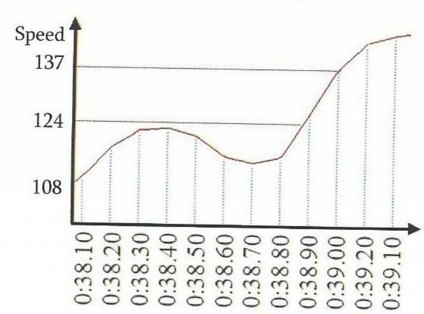


Figure 1.19 *The final curve after digitization of the channel.*

Logging Rate

Taking single data points and connecting them with a line always creates some amount of error. The faster these data points are logged the more accurate the resulting curve will be to the original. Below are two examples:

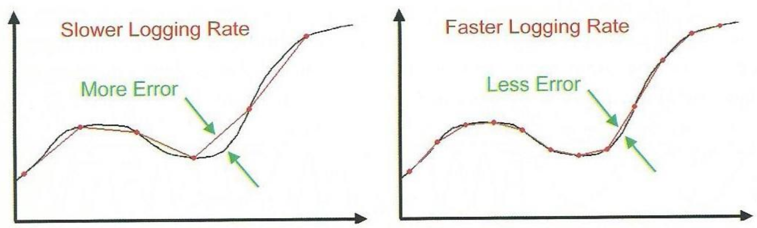


Figure 1.20 *More accuracy can be achieved by logging faster.*

Each channel gets logged at some fixed rate, which may be different from other channels. The term *rate* is the frequency of occurrence and refers to the number of data points per second. Frequency has a unit of Hertz or Hz for short. If you log a channel at 10 times a second, you are logging at 10 Hz. Logging at 200 times a second is a rate of 200 Hz.

Films in a movie theater are recorded at only 24 Hz. This means 24 frames or still images are shown on the screen per second. Yet the motion looks fluid and continuous. This is a limitation of the human eye and our ability to process images.

The logging rate chosen for each channel of information will depend on how quickly that channel changes value. The temperature of engine oil doesn't change very often, perhaps only a degree or two during a time period of one minute. Therefore that channel can be

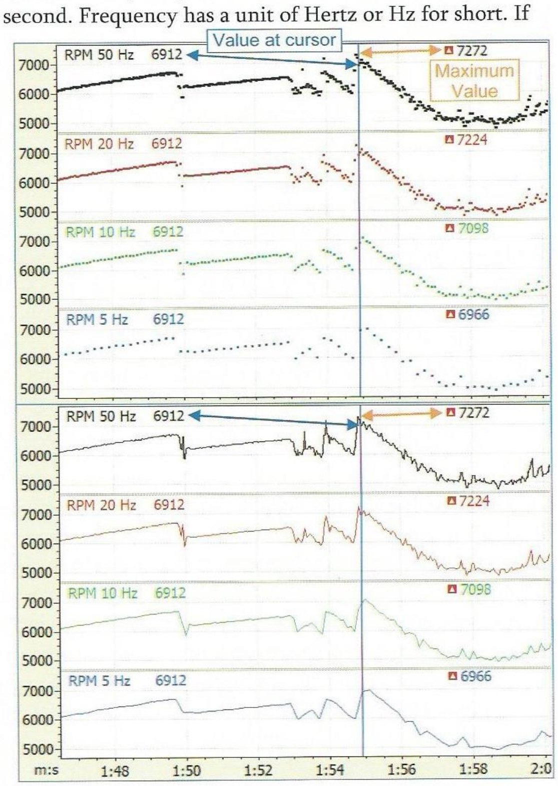


Figure 1.21 *The same data logged at different rates. Notice the true maximum RPM occurs just to the left of the cursor and is missed at slower logging rates.*

sufficiently logging at 1 Hz. But a suspension sensor which measures the movement of the dampers would change very quickly as the suspension navigates over many bumps through the same time period of one minute. Suspension sensors should be logged at a minimum of 200 Hz.

△ Warning: Always be aware that a channel's value could be changing more quickly than it is being logged. If you suspect this from a channel, increase the logging rate and compare the new faster data to the old slower data. For example, Engine RPM should be logged at a minimum of 20 Hz as shown in ***Figure 1.21***.

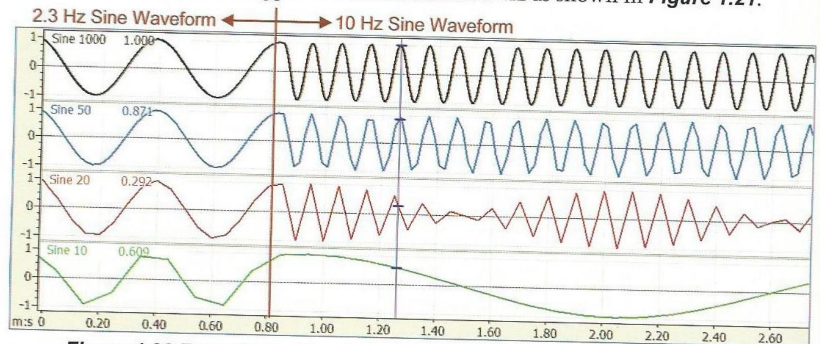


Figure 1.22 *Four different logging rates of the identical sine wave show how slower logging rates can corrupt the actual waveform.*

Logging Memory

While faster logging rates will lead to increased accuracy, more memory is required to record all those additional data points. And the law of diminishing returns kicks in at some rate when there becomes no useful advantage to logging faster. Either the sensor does not update quickly enough or the resolution can't see any smaller changes in measured values from one data point to another.

The amount of memory a logger has is typically expressed in MegaBytes (MB). Data loggers can calculate how much actual logging time is available.

$$\text{logging time} = \text{memory} / (\text{channel}_1 * \text{log rate}_1 + \text{channel}_2 * \text{log rate}_2 + \ldots)$$

You don't have to remember this equation, only know that the more channels you log and the higher the logging rates, the less time there will be available to record data. This becomes important if the logger is going to run out of memory before the end of the race or practice session. Consider having one setup for practice where channels are logged faster for increased accuracy, and one for the race where logging rates are turned down to increase logging time.

Logging Start / Stop

One thing that can help is a programmable start and stop condition for when to log. Some data systems have predefined conditions based on RPM or speed. Some allow the user to control when to start and stop logging. One possibility is to start logging whenever Engine RPM is greater than zero. This will record all the time spent warming up the engine at idle. Another possibility is to set the start condition to log whenever the car is moving based on the speed channel.

1.4 Data Display Types

Graph

The word *graph* is a generic term referring to data being displayed in many different ways. But in racing, a graph refers to a display of data with respect to time or distance on the x-axis. The y-axis will be the logged channel value. It can also be called a time or distance plot.

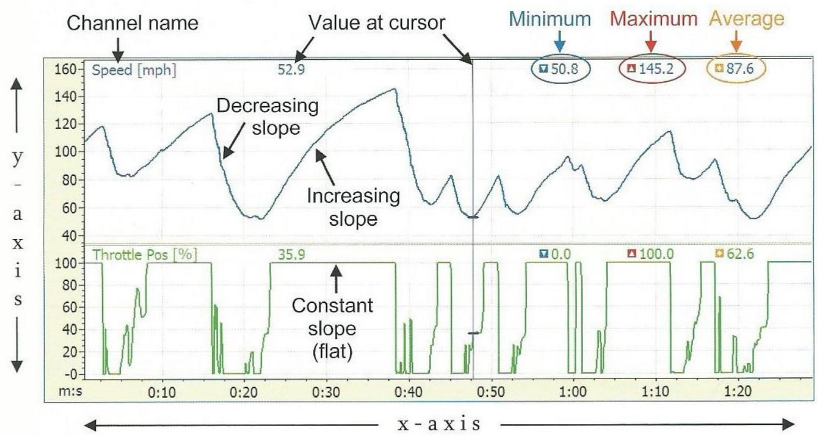


Figure 1.23 *Graph, also known as a time or distance plot.*

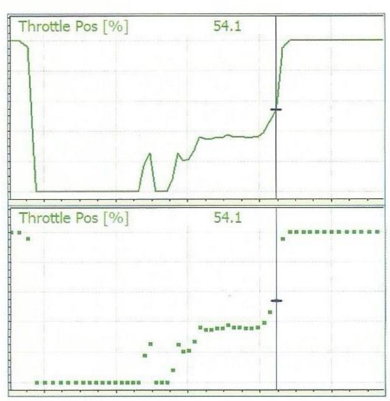


Figure 1.24 *A trace is created by joining the data points with a line.*

Graphs get created from single data points but with lines connecting each one. This creates the *curve* also called a *trace*. Straight lines are used most often to connect the dots, which assumes the channel moves linearly between each data point. This is a reasonable assumption provided the logging rate is fast enough for that channel.

Data points can be thought of as words, and when connected with a squiggly line they tell a story. Graphs allow for quick visual analysis of trends and movements which cannot be seen through a simple list of channel values, as shown in ***Table 1.1*** a few pages back. While many other data display types might illustrate single characteristics of the data more clearly, none display more information than what can be extracted from looking at squiggly lines on a graph.

X-Y Plot

Outside of racing, a graph may have any parameter on the x-axis. In racing, if the x-axis has anything other than time or distance, it will be called an *X-Y plot*. The X-Y plot may use lines to form a trace, but can also be composed of only dots or circles. The most common X-Y plot is the G-G diagram. Additional colors on the data points can be used to convey another channel of information. Throttle position is shown below with a gradient color scale where blue is 0% and orange is 100%.

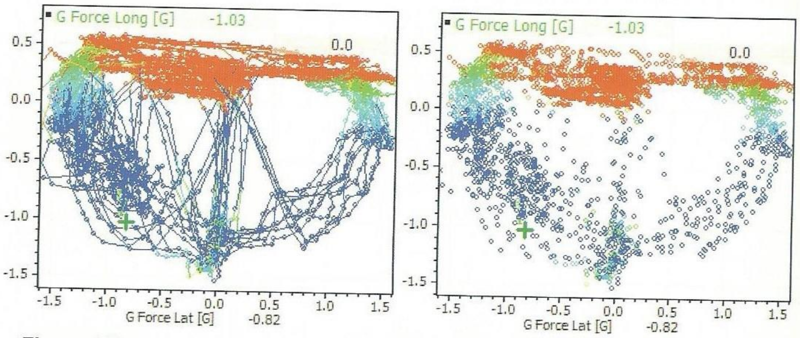


Figure 1.25 *X-Y plots don't have time or distance on the x-axis. They can be joined with lines as on the left or plotted with circles as on the right.*

Report Tables

Statistical analysis techniques can be used on each channel and reported in a table. Often used for engine health related channels, these statistical reports provide the minimum, maximum or average values for each channel.

		Mid-Ohio, Driver X, GT Sedan							
		Lap 1 [1:29.785]	Lap 2 [1:30.124]	Lap 3 [1:30.028]	Lap 4 [1:29.984]	Lap 6 [1:32.720]	Lap 7 [1:30.110]	Lap 8 [1:29.750]	Lap 9 [1:29.527]
Corr Speed [mph]	Max	144.4	142.4	145.0	144.2	142.4	144.8	143.7	144.6
Engine RPM [rpm]	Max	9114	8952	8958	9384	9090	9078	9402	9330
Engine Temp [°F]	Max	172.4	176.2	173.1	173.1	171.9	174.6	175.1	169.2
Eng Oil Temp [°C]	Max	102.8	104.4	105.2	106.8	99.8	104.7	106.3	107.0
Eng Oil Pres [psi]	Min	53.68	50.92	49.55	49.88	58.44	51.36	47.62	48.71
Fuel Pres [psi]	Min	70.25	70.25	70.15	70.25	70.15	69.98	69.98	70.06
Fuel Used [USgal]	Val Chng	0.441	0.438	0.451	0.450	0.428	0.446	0.443	0.447

Table 1.2 *Channel reports contain statistical information. Here the channel maximums are in red boxes while the minimums are in blue boxes.*

Histogram

A Histogram adds up the time a channel's value falls into a specific range. The range is called a *bin*. These ranges are labeled on the x-axis. The height labeled on the y-axis will represent either actual time or a percentage of total time.

In its most simple form, a histogram can be shown in text only as in ***Table 1.3***. But this does not add much visualization to the data. So histograms are normally displayed with either bars or lines. The taller a bar or line, the more time spent in that range or bin.

Engine RPM	Time (s)
	Lap 9
6000...<7000	0.50
7000...<8000	0.10
8000...<9000	0.30
9000...<=10000	0.10

Table 1.3 *Text histogram for RPM over a 1 second period.*

The most common type of bar histogram is engine RPM, which displays how much time is spent in each RPM range. This can be useful for engine builders and tuners. Using our previous example of logged data from ***Table 1.1***, all histograms on this page divide engine RPM into 4 specific bin ranges; 6000-7000, 7000-8000, 8000-9000 and 9000-10000. The table reports 10 data points totaling one second of logged data. Therefore adding up each bin value will equal the total time.

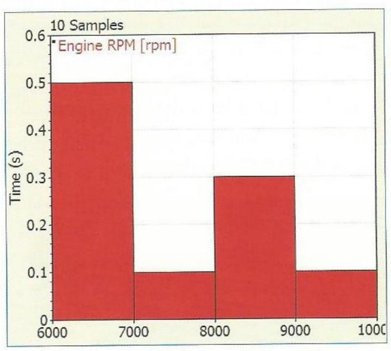


Figure 1.26 *Bar histogram for engine RPM over a 1 second period.*

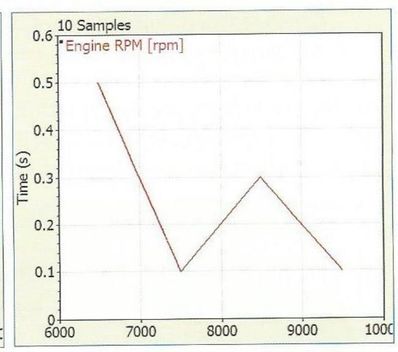


Figure 1.27 *Line histogram for engine RPM over a 1 second period.*

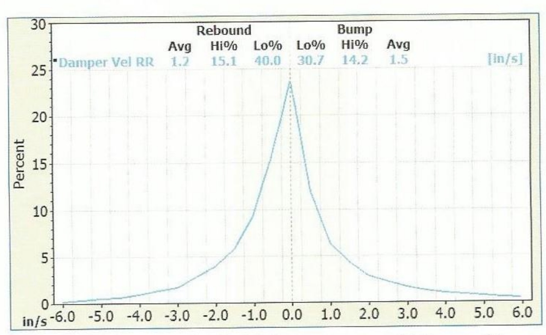


Figure 1.28 *Damper velocity histograms are widely used in racing. It reports the percentage of time spent at each velocity the damper moves and is useful for tuning damper settings.*

Chapter 2 Speed

Speed is the essential holy grail to data analysis. It is the most important channel to log. The channel of speed is probably used in 80% of all analysis work done by the engineer. Using speed alone, you can do the following:

- identify straights and corners
- analyze braking points
- determine braking effort
- set brake bias from wheel lockups
- evaluate car setup based on cornering speeds
- compare driving lines through a corner
- locate areas of throttle lift
- find traction problems out of corners
- evaluate aerodynamic effects

Any place where a driver can increase their speed will result in a lower lap time. Comparing speed between laps and with other drivers will be the most powerful analysis tool you have.

Knowing where a driver is slow on the race track is half the battle. Getting a driver to change their actions to improve is the other half. Usually there are only one or two corners where most of the time is being lost, not every corner. If the driver tries to go faster in a corner where he or she is already at their maximum, a crash is to be expected. For this reason, it's important when coaching a driver to show them where they have room to improve and where they don't.

Figure 2.1 *There's nothing more frustrating than mowing grass on a weekend. Avoid off course excursions by knowing where you can and can't go faster.*

The units of speed, mph for miles per hour or km/h for kilometers per hour, represents how the channel is calculated. It is made up of distance over time in the simple equation:

$$\text{Speed} = \text{distance} / \text{time}$$

In other words how many miles can be traveled in a period of time? Lets take a look at how this channel gets measured on a race car.

Many different ways to measure speed exist. Some methods include counting wheel revolutions, optical ground sensors, GPS receivers and pitot tubes. Each one has its advantages and disadvantages. The most common method is an axle with teeth used to count wheel revolutions. The second most common method is using a GPS receiver. Both of these will be discussed in this chapter.

2.1 Speed from Tire Revolutions

Knowing the circumference of a tire and how many revolutions it made, the *distance* a car traveled can be calculated. It is accomplished with a sensor that counts tire rotations and informs the data logger of this information. Measuring how long it took to travel that distance provides the *time*. The data logger uses an internal clock to measure the time it took. Both *distance* and *time* are used to calculate the speed of the car.

Waiting for the tire to make a full revolution takes too long and therefore results in a very slow update rate. So multiple triggers, also called *teeth*, are put on the hub or axle. The sensor triggers on each one as it passes by. Now the calculation for speed can happen more often than once a revolution. While 6 teeth should be considered the minimum, 12 to 24 teeth are highly recommended. Most street cars with ABS or traction control use a minimum of 48 teeth per revolution. Some newer models have up to 100 magnetic triggers located in the shield of the bearing which the sensor triggers from. The more teeth, the faster the update rate. But having too many teeth might cause the sensor to reach its maximum switching frequency and stop working.

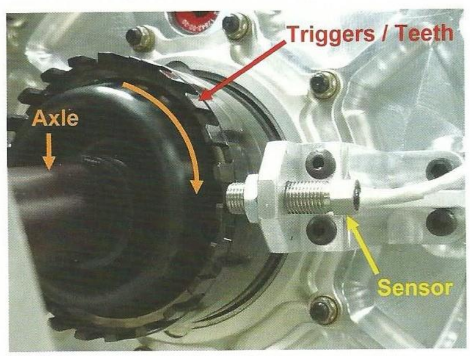


Figure 2.2 *Each tooth triggers a voltage change in the sensor, which allows the data logger to calculate speed.*

The logger calculates speed after each tooth passes by the sensor using the following equation:

$$\text{Speed} = \frac{\text{tire circumference / \# of teeth per revolution}}{\text{time between teeth}} = \frac{\text{distance (miles)}}{\text{time (hour)}}$$

Unfortunately, this speed measurement is prone to errors. While the logger calculates a very accurate time from its internal clock, the rolling circumference is always changing while on the race track. The tire which flattens to form the contact patch, gets pushed and pulled in all directions; forward, backwards and sideways. A tire's circumference is therefore continuously changing throughout a lap due to the following effects:

- Centripetal forces from a tire's rotational speed
- Static load from vehicle weight
- Dynamic squish from load transfer when braking or cornering
- Temperature and pressure changes

Every tire has a different reaction to these forces based on its internal construction. Radial tires have cords inside that restrict longitudinal strain much more than bias ply tires which have its cords laid at an angle. The circumference of a radial tire might vary by 1%, while bias ply tires can change up to 3%. But even 1% at 160 mph results in a 1.6 mph error. I've seen driver's complain they are down on engine power and request an engine change because of 1.6 mph.

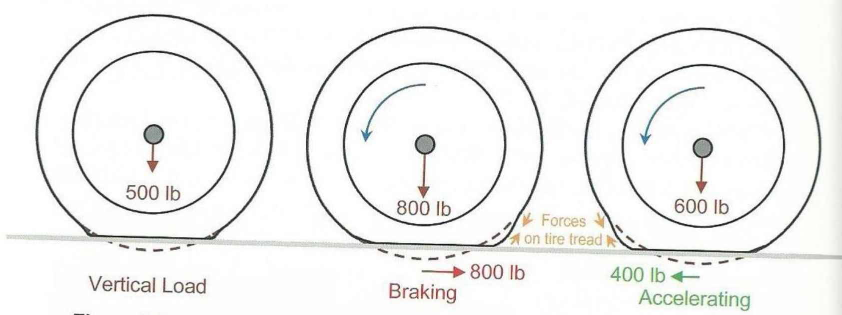


Figure 2.3 *Tire circumference changes whenever forces are applied to the tire.*

△ Warning: Most people measure tire circumference while the tire is off the car using a piece of string wrapped around the center of the tire. But this generates too large of a number. Once the tire gets put onto the race car, the weight of the car squishes the tire down to a smaller radius. So the best method to measure tire circumference is:

1. Start by marking the tire and ground with chalk where they touch.
2. Then roll the car forward until the mark rolls back to the ground and mark that point on the ground.
3. Measure the distance on the ground between both marks.

This number should be entered into the data logger for tire circumference. Some might argue the tires should be set to their normal operating pressure when rolling on the car instead of their cold pressures. If you want to take that extra step go ahead, but that amount of error is generally small enough not to worry about.

☑ Check: If your race car has bias ply tires, the circumference must be measured with each set. Some teams will measure their tires again after the scrub in period. For radial tires the same number can generally be used for multiple sets while still maintaining a typical engineering margin of error.

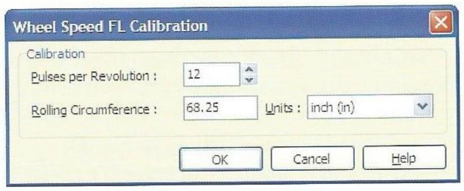


Figure 2.4 *Data loggers have a calibration setup where teeth count and tire circumference are entered.*

One of the largest sources of speed errors can come from longitudinal slip of the tire on the pavement. The sensor and trigger system have no clue to the actual speed of the car, they only measure tire rotation. Three situations can occur where the tire rotation does not match the speed of the car. They are:

1. Acceleration: when the driven tires break traction they start spinning faster than the true speed of the car.
2. Braking: the car is moving but the tires are locked up from too much braking force. Obviously a situation that should be avoided as this will cause flat spots on the tire.
3. When turning a corner, the length traveled by the inner and outer radius changes the measured speed, and an average is the true speed of the car.

Ground Speed & Drive Speed

Most racing cars have four wheels and therefore should have four wheel speed sensors (FL, FR, RL, RR). Having four wheel speed sensors is imperative for analyzing brake lockups and traction problems. But for most of our analysis, a single speed channel is all that's needed. So which wheel speed channel should be used?

To start, lets separate the rolling wheels from the driven wheels. The term ground speed will represent the rolling wheel speeds. This will be the fronts on a rear wheel drive car, or the rears on a front wheel drive car. The term drive speed will represent the driven wheel speeds. This will be the rear for a rear wheel drive car, or the front for a front wheel drive car.

Drive speed is always subjected to longitudinal tire slip during acceleration. Even when the tires don't appear to be slipping during acceleration, they are! Under normal acceleration 1-4% of forward slip is normal, and up to 8% before a driver starts to complain of traction problems. Because the wheel spins with any percentage of slip, the sensor reports a higher speed than the true speed of the car. This makes drive speed a poor choice for analyzing speed.

Ground speed channels simply roll with the vehicle as it travels forward. Rolling wheels therefore provide a more accurate speed measurement because they are not constantly slipping during acceleration. The only time rolling wheel speeds become problematic is during brake lockup. This factor becomes important when selecting how the two rolling wheel speeds (FL and FR) should be combined when creating a single speed channel for analysis. Three options exist; the fastest, the slowest or an average of both.

One observable fact to remember is the radius differences between the inside and outside tires during a corner. When the car is turning, the inside tire must rotate slower as it is forced to cover a smaller distance. The outside tire spins faster as it follows a larger arc. So the inner tire reports a speed that is slower than the true speed of the car, while the outer tire reports a speed that is faster. The true speed of the car is an average of the two tires. This effect gets larger the tighter the corner. In Turn 11, also known as the hairpin of the Long Beach Grand Prix circuit, speed differences between the inner and outer lines will reach 10%.

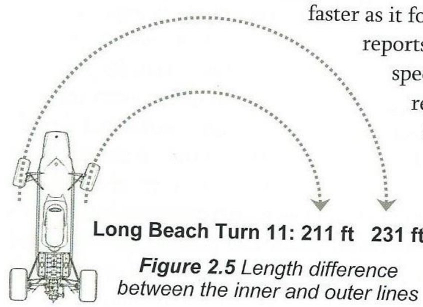


Figure 2.5 *Length difference between the inner and outer lines*

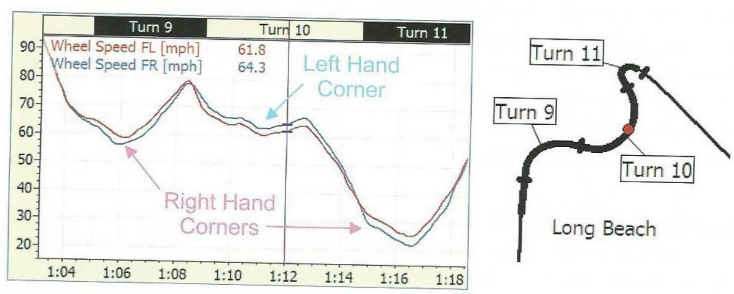


Figure 2.6 *Wheel speeds vary based on the inside and outside radii when a car travels around a corner.*

While an average of both is most accurate, many times this averaging becomes problematic when brake lockup occurs. A brake lockup is when the braking system over powers the rolling tire and cause it to slow down (partial lockup) or in a worst case scenario stop spinning completely (full lockup). Road courses feature heavy braking zones so lockups are common. Trail braking is also a major contributor to the inside tire locking up during corner entry.

Taking an average of both wheel speeds would therefore introduce errors from one tire locking up. When calculating the distance traveled for each lap around the track, these errors add up with each braking zone. This makes analyzing and comparing data very difficult because the traces won't align correctly due to an inaccurate distance being calculated. And it is just as important on cars with ABS because the anti-lock braking systems do allow for small partial lockups.

The best method for road courses is to use the fastest rolling wheel speed, not an average. *The advantages in accuracy from averaging do not outweigh the reliability and consistency of selecting the fastest.* This is the most important consideration when distance is used to line up traces of data from different laps.

The fastest method is also the best for front wheel drive cars, whose inner rear tire tends to lift off the ground during heavy cornering. This situation results in a slower speed measurement as the tire spin slows down when it is up off the ground.

Wheel speed sensors can get knocked off, damaged and sometimes stop working in the middle of a race. Another reason why the best solution for road courses is the fastest rolling wheel speed.

An oval track is the one circumstance where an average of both rolling wheel speeds should be used. Ovals are not subjected to wheel lockups caused by heavy braking. This takes away the consistency argument. And secondly, cars spend a higher percentage of time cornering. This increases the percentage of error in lap distance when using the fastest. *Therefore accuracy rather than consistency of lap distance is more important during analysis on oval tracks.*

When using an average method, make sure there is a limit function built into the logger's calculation. A limit function will switch the ground speed calculation from average to fastest when the difference between the two individual wheel speeds exceeds a set percentage. If a wheel speed sensor does stop working during the race, the data logger will automatically switch to the good wheel speed sensor rather than averaging the non working sensor with the working one.

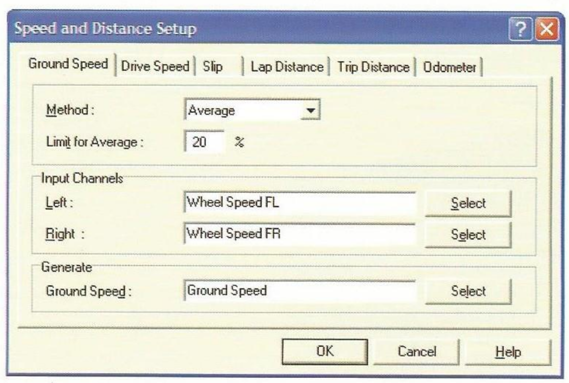


***Figure 2.7** The data logger should have a setup window for Ground Speed where the method for combining two wheel speeds is chosen.*

△ Warning: Accuracy of speed is severely limited if only one wheel speed sensor is installed on the car. Two wheel speed sensors is always better than one! Remember to use rolling, not driven wheel speeds!

Corrected Speed

As seen in ***Figure 2.8*** below, it is possible for both wheels to lockup under braking. After downloading the data, some analysis programs can apply a G Force correction. This can make use of the longitudinal accelerometer to calculate what the speed of the car should be while both rolling wheels are partially or fully locked. This new channel is called Corrected Speed and can be used for calculating an even more accurate lap distance. It is abbreviated as Corr Speed. When analyzing data use Corr Speed for the most accurate speed when the analysis requires only a single speed channel. If that channel isn't available in your analysis software, then use Ground Speed instead.

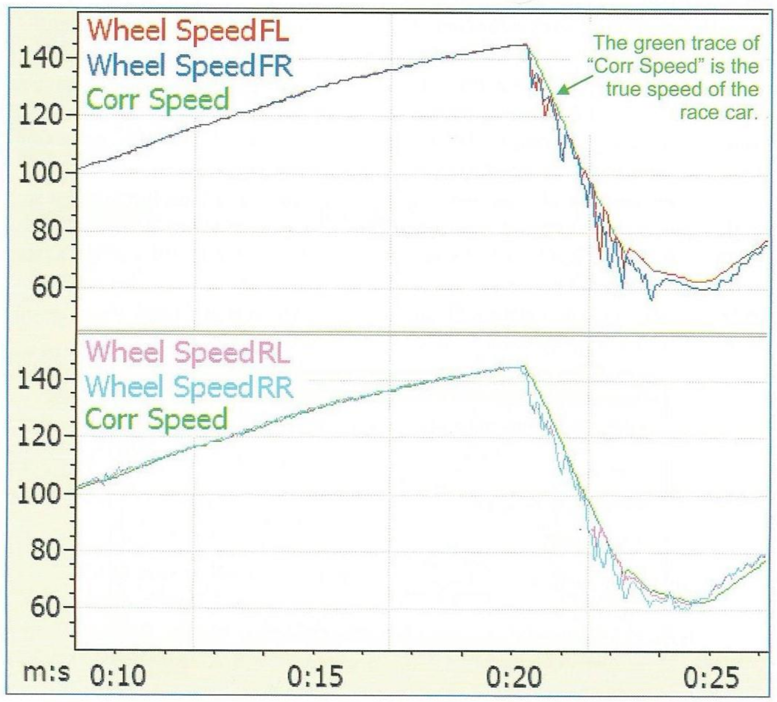


Figure 2.8 *Maximum braking on a race car with ABS. As the individual tires begin to lock up they measure less speed than the true speed of the car.*

2.2 Speed from GPS

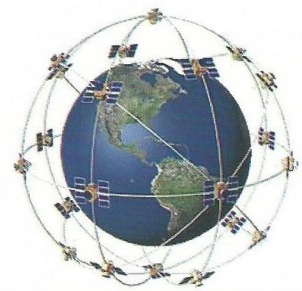


Figure 2.9 Multiple satellites circle the globe in their orbits.

Because GPS receivers have dropped in price, a plethora of low end data acquisition systems based solely on GPS have been released into the marketplace. These low cost data loggers are helpful for bringing data acquisition to the weekend track junkie warrior. For the price of a new set of tires, a data logger can provide many more seconds of lasting improvement!

With all these potential problems with wheel speeds, why not use GPS for speed? Speed from GPS does have its own issues. So rather than being the sole source of speed measurement, GPS should be used to compliment a full set of four wheel speed sensors. Lets look at the difficulties and reasons why GPS should not be your main source for speed.

GPS Update Rate

The hand held GPS devices commonly used for hiking or automotive navigation update at 1 Hz, which is only once a second. This is simply not practical for high dynamic environments such as motorsport. While 5 Hz units are acceptable for positional data, the minimum that should be considered for speed measurement is 10 Hz. Wheel speed sensors can easily update at 100 Hz with enough teeth.

Many low cost data systems rely on GPS receivers which update at only 4 Hz or 5 Hz. To supplement this slow update rate, internal accelerometers are used to fill in the gaps of data. Through various math equations, the internal accelerometers help in generating a faster updating speed channel, as well as providing rejection criteria for bad GPS data. While they do lack in terms of accuracy and consistency, such data can still be quite useful for analyzing both a driver and the car.

Figure 2.10 Professional GPS units have a receiver box and separate antenna. The location of the antenna is very important to attaining good GPS data .

GPS Drop Outs

There is also an issue on many race tracks with bridges. When a GPS receiver travels under the bridge, it loses site of almost all the satellites up in the sky. The measurement of speed drops to zero and can take up to a full second to reacquire those satellite signals when it emerges from the other side. Even small foot bridges can cause problems. As the satellites move in their orbit during the day, varying amounts of errors are experienced throughout the day. A small foot bridge might be fine in the morning but drop out in the afternoon. Besides bridges, even canopy coverage from trees pose a problem. At the Lime Rock circuit in Connecticut trees hang over the exit of the last turn. The number of satellite signals drop because half the sky is covered by trees. Then on street circuits like Long Beach or St. Petersburg, the tall city buildings block much of the sky also causing drop outs.

GPS Accuracy

Accuracy is based on the number of quality satellite signals the receiver can find. It must have direct signals and not multi-path signals which are those that bounce off walls or other surfaces. For this reason, always mount the antenna on top of the car with a nice ground plane and away from other antennas.

△ *Warning:* When using any GPS system, always play your role of detective in identifying bad GPS data. Most erroneous data comes from low satellite count. Luckily GPS systems will also report the number of satellites used, While every GPS system is different, most will need at least 8 satellites to produce accurate results worthy of analysis. Many also provide a channel called HDOF or horizontal dilution of precision. This reports an estimate of accuracy and updates continuously with each GPS data point.

GPS Time Delays

△ *Warning:* Sensors connected directly to the data logger such as steering or throttle, have very little to almost no time delay in their data being logged. But both position and speed data from a GPS receiver will incur time delays of 0.10 to 0.25 seconds before being logged. These delays come from the GPS receiver's calculation and the serial transmission of that data to the logger box. This time delay will shift the traces and your data won't be synchronized between other channels. A typical 5 Hz GPS unit going 100 mph will result in a 36 foot offset of position. Always apply a time offset correction in the analysis software to shift the data points back so they correspond in time with sensors connected directly to the data logger.

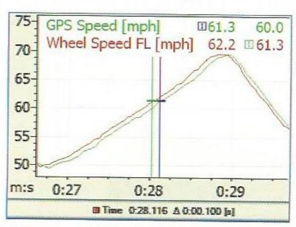


Figure 2.11 *GPS data lags in time compared to a directly connected sensor.*

GPS Summary

Technology is always advancing. In 2006 the price of a 10 Hz GPS unit went from $6000 to $1000. This new low cost unit tracks up to 12 satellites and utilizes differential corrections (DGPS) based off geosynchronous satellites. Also called WAAS or SBAS corrections. All GPS receivers used in motorsport must have DGPS built in. While a 5 Hz unit can be found for as little as $300, it's best to spend the extra money and get a true 10 to 20 Hz update rate. In the future GPS receivers will update faster, track more satellites and provide better accuracy. When that happens GPS will become a reliable source for speed data.

Time vs. Distance

After downloading, the entire logged data set will likely be composed of an out lap, multiple timed laps and an in lap. Along the horizontal or x-axis will be either time or distance. Along the vertical or y-axis is speed. The path of the trace is not some random squiggly line. It moves up and down in a pattern as it follows the straights and corners of the track lap after lap.

When displaying graphs, always be aware of the x-axis. Is it in time mode or distance mode? If the x-axis is switched from time to distance, the areas where the car is slower compresses, while the areas where the car is faster expands.

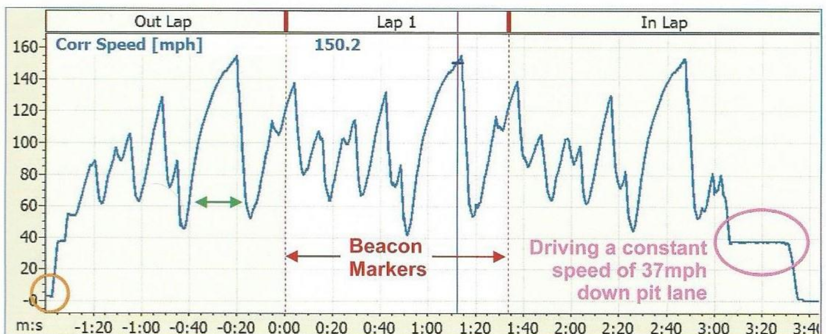


Figure 2.12 *A full outing graph at Road Atlanta of speed shown in time mode.*

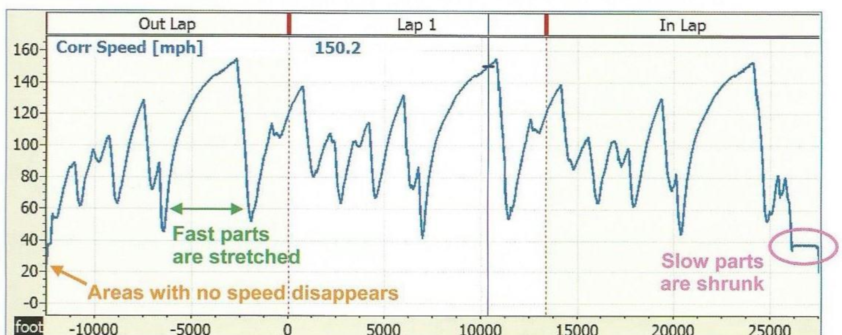


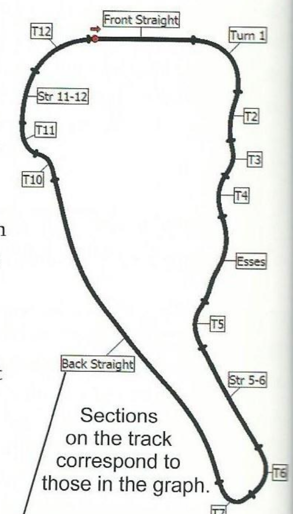
Figure 2.13 *Same full outing graph of speed shown in distance mode.*

△ Warning: Any logged data being recorded while the vehicle is not moving, simply disappears in distance mode because there is no distance being travelled when the car is stopped. It is important to have a good understanding of how the logger calculates distance for each lap, and the pitfalls that can be encountered as were discussed previously when choosing a method of calculation for a single speed channel.

2.3 Speed Graph

Many things can be identified from a brief look at the speed trace. The first example is a graph from a single lap around the Road Atlanta circuit located in the state of Georgia. Each section is called out along the top of the graph, corresponding to the names of sections found on the track map. The minimum, maximum and average speeds are reported in the upper right corner for the visible data shown in the graph. Three vertical lines (called cursors) in the graph below represent in order from left to right; the user movable cursor location (blue), the minimum value location (also blue) and the maximum value location (red).

1. The trace goes in time from left to right where the start of the lap is located at the far left. It will correspond to where the beacon lap marker is located. This should be but might not be the official start / finish line.
2. Each local valley in the trace will be the minimum cornering speed of that turn.
3. The cursor sits here on a local peak. It is the maximum speed along the straight before Turns 6. The value at the cursor is reported in the graph label found in the upper left corner, where Corr Speed has units of mph.
4. In this region the trace is decreasing (negative slope) while the driver brakes for Turn 6. Then accelerates a little before getting on the brakes again for Turn 7 (minimum speed of lap).
5. The easiest thing to locate should be the longest straight. (longest section of time spent accelerating) At Road Atlanta the back straight is where maximum speed is found.
6. The longest braking zone is identified by the largest single drop in speed.
7. The end of the lap is located at the far right.



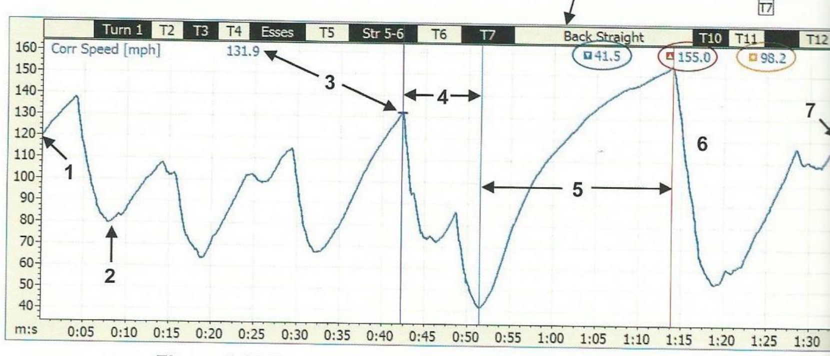


Figure 2.14 *Overview graph of a single lap at Road Atlanta.*

Below is a more detailed description of the same lap around Road Atlanta. Learning to identifying each of these discoveries is the goal of this chapter.

1. Here the car is accelerating down the front straight reaching a local maximum speed just under 140 mph. Notice the slope is positive or upwards.
2. The braking zone for Turn 1 reports a speed drop from 140 to 80 mph. Notice the slope is negative which travels down.
3. The minimum speed through Turn 1 was 80 mph.
4. The speed starts to climb exiting Turn 1, but pauses at this point. The driver started to apply throttle, but must have backed off for some reason. This is called a throttle lift. Ask the driver why!
5. Here the trace has a smaller hesitation, more likely caused by a gear shift or very small throttle lift. Examine the throttle and gear traces to find out.
6. A very short tap on the brakes for Turn 2.
7. A longer and steeper braking zone for Turn 3.
8. Less slope near the end of this braking zone is caused by trail braking where the amount of braking decreases while steering angle is added.
9. Going through the Esses, the slope shows a small period of braking. Then back to accelerating up to 115 mph before heavy braking for Turn 5.
10. A momentary release of the brakes likely in response to wheel lockup from too much braking. Individual wheel speeds should be investigated.
11. This local minimum for Turn 6 doesn't have a normal shape. The trace increases a very small amount, then decreases. The driver got on the throttle too early and needs a better driving line through this corner. More channels and driver feedback are needed to further analyze this.
12. A normal corner shape with a smooth exit heading down the longest straight.
13. A total of 4 gear changes occurred down the back straight. Shifts happen where the slope in acceleration changes. Acceleration decreases in each higher gear due to a lower gear ratio and increased aerodynamic drag.
14. This increase in acceleration is from a downhill section of the track. Knowing all track elevation changes can help explain why the slope increased.
15. S-turn complex of Turns 10 & 11.
16. Accelerating onto the main straight.

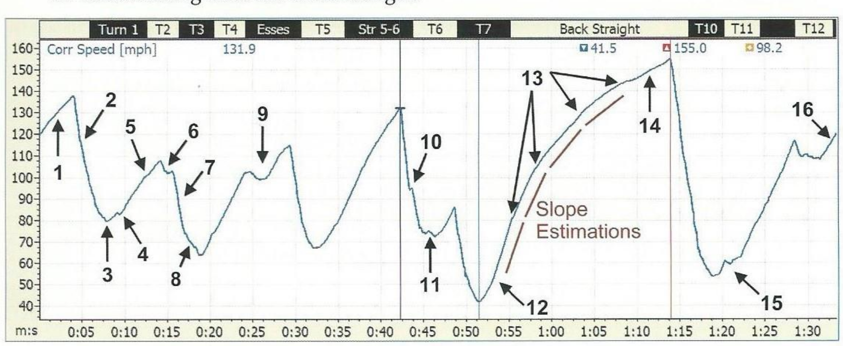


Figure 2.15 *Detailed analysis of a single lap at Road Atlanta.*

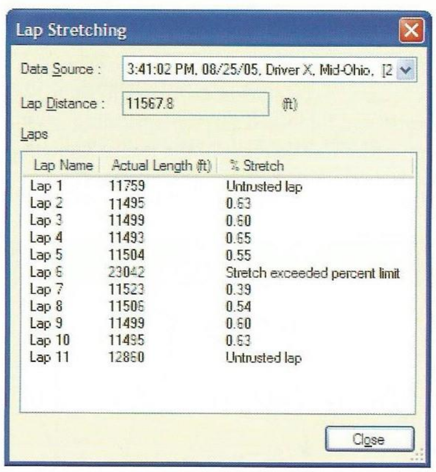
Calculating Distance

The most important calculation derived from the speed channel is the distance a race car has driven each lap. Not the total number of miles driven, but the calculated lap distance. It is used on the x-axis every time two laps are compared. If the lap distance is wrong it can be impossible to compare two laps because they won't line up and overlay correctly. The calculation uses a mathematical function called *integrate*, which turns speed into distance.

Lap Distance

It is nearly impossible for two laps to have the exact same lap distance due to variations in the line driven around the race track. The ever changing rolling tire circumference also contributes to this variation. Even so, most laps will fit within a 2% variance. If starting a session with very low tire pressures, the lap distance report will show an evenly decreasing distance lap after lap as the pressure comes up in the tire causing it to get bigger. The racing line driven in the rain will also differ from a dry line. Out laps and in laps are even further off due to driving down pit lane instead of the race track. Also note, there will be many tracks where the driven race line will not equal the official track distance.

To help correct for these types of problems during graph overlays, the laps being compared should be stretch or shrunk to exactly the same distance. Such a function is required to compare time variance between the two laps, a topic discussed later in this chapter. Many software programs will stretch laps automatically without notice to the user. If possible review all lap distances to look for any abnormalities that could effect analysis.


Lap Stretching

Data Source : 3:41:02 PM, 08/25/05, Driver X, Mid-Ohio, [2

Lap Distance : 11567.8 (ft)

Laps

Lap Name	Actual Length (ft)	% Stretch
Lap 1	11759	Untrusted lap
Lap 2	11495	0.63
Lap 3	11499	0.60
Lap 4	11493	0.65
Lap 5	11504	0.55
Lap 6	23042	Stretch exceeded percent limit
Lap 7	11523	0.39
Lap 8	11506	0.54
Lap 9	11499	0.60
Lap 10	11495	0.63
Lap 11	12860	Untrusted lap

Close

Figure 2.16 *Lap distances of an outing.*

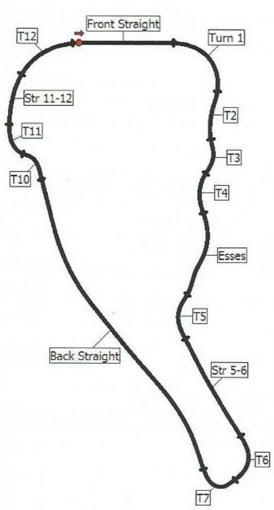
In the example of ***Figure 2.16*** notice the in and out laps are longer than the normal circuit laps. Out laps and in laps should be excluded from any stretching as they will never line up correctly. Also notice Lap 6 is about twice the normal length. This must have been two laps, an in lap and out lap where the car missed the beacon lap trigger because it drove down the pit lane and not on the race track.

Each data system has its own method for calculating distance, usually from one or two wheel speed sensors. Some have only GPS data to use. It is important to know which method is being used.

2.4 Overlay

With distance being calculated accurately, it will now be possible to compare different laps either from the same driver or between different drivers. Laps are shown on the same graph creating what is called an overlay of one lap on top of another. The faster lap is typically overlaid onto a main lap of interest. The comparison of speed between two laps and/or with different drivers is the **quickest and most important** graph to analyze.

1. The black trace is above the blue trace, which represents a faster speed. The overlay lap is faster down the front straight and while braking for Turn 1.
2. While the speed out of Turn 1 is the same, the difference in curvature at the middle of the corner signifies that a different racing line was driven.



3. Minimum cornering speed and exit speed is much slower for the blue trace.
4. The driver of the black trace is much faster with only a lift through the Esses, while the driver of the blue trace uses the brakes.
5. Braking, minimum speed and exit are all similar here.
6. The driver of the blue trace lost more time by over slowing in both Turns 6 and 7.
7. Speeds down the back straight are identical.
8. Braking for Turn 10 is almost identical.
9. The slow driver (blue trace) is finally faster in the middle of Turn 10, but is horribly slow coming off Turn 11. There is a 5 mph deficit heading towards Turn 12 and onto the front straight. Always have the driver explain in their own words what is going wrong, before making conclusions.

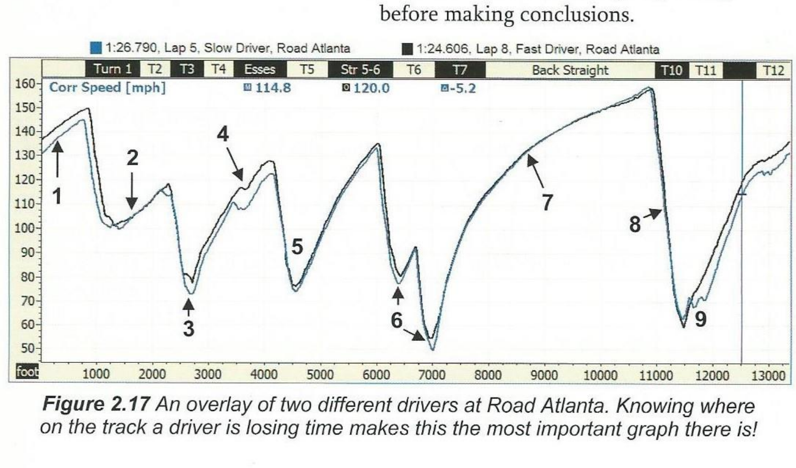


Figure 2.17 *An overlay of two different drivers at Road Atlanta. Knowing where on the track a driver is losing time makes this the most important graph there is!*

2.5 Variance

An overlay of two laps is great for finding where the speed differences are, but it does not tell you how much time was lost or gained in each area. For that we turn to variance, also known as time-difference. It will show you where one driver is faster than the other and by how much. The variance calculation finds the time difference between two laps at any given lap distance. This calculation is done continuously throughout the lap giving a cumulative difference in time.

In the example shown below in ***Figure 2.18***, the variance is graphed comparing the main lap in blue versus the reference lap in black. At the start of a lap the variance is zero as both laps haven't traveled any distance. The variance at the end of the lap will be equal to the difference between each lap time. At the cursor location, the main lap in blue reaches 12,500 feet in 1:16.777 and the overlay lap in black gets to the same distance in 1:14.764. Therefore the overlay lap is 2.013 seconds faster at that location on the track.

Examples of conclusions made from each section as marked with numbers in the graph is as follows:

1. 0.4 seconds lost, most of it in the braking zone.
2. Speed is the same out of turn 1, so the variance is flat does not change.
3. 0.5 seconds lost by the blue trace through this entire section.
4. 0.5 seconds lost while braking and over slowing in Turns 6 & 7.
5. Speed down the back straight is the same, so the variance doesn't change.
6. Notice the higher minimum speed for the blue trace in turn 10 shows up with a small gain in variance for the blue trace.
7. 0.7 seconds lost from Turn 11 through the end of the lap.

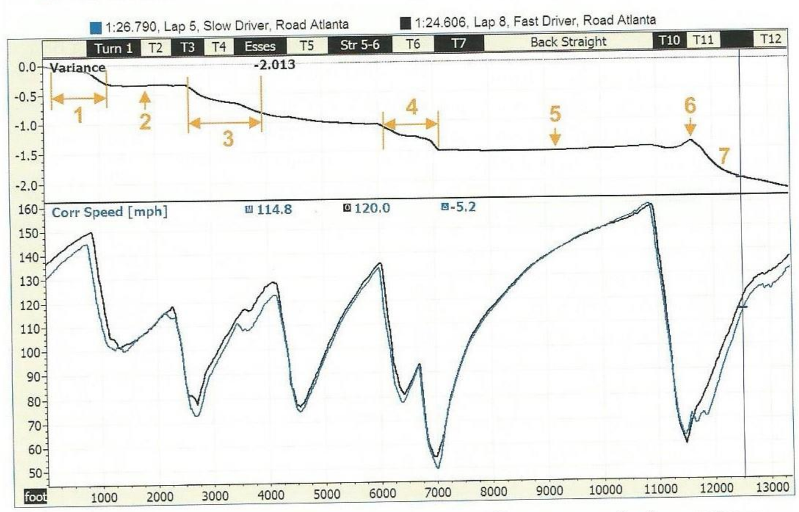


Figure 2.18 *Differences in speed lead to a time difference, graphed as variance.*

Remember, if a driver is one second off the pace they should not go out and try to make up that full second in every corner. If they attempt to, then a lack of talent will present itself in the form of an off course excursion, spin or crash. Instead, use variance to find out which corner needs the most improvement and get the driver to focus on improving one corner at a time.

All you have to do is look at where the variance goes up or down to find areas of concern. By looking at the values both before and after a section, you can subtract the two numbers to find the time gained or lost in that section. Variance will correspond directly with any differences in the speed traces. Anywhere the variance is changing, the speed traces will be different.

☑ Check: Whenever comparing different laps of data, distance should be along the x-axis and lap stretching must be active in the software. Lap stretching shrinks or expands the laps a small percentage so that both laps have the same total lap distance. Without this, the final variance at the end of the lap won't match the lap time difference between the two laps.

Real Time Lap Predictor

Many data systems have a built in lap predictor also called lap gain/loss. It provides real time feedback for the driver if he or she is going faster or slower than a chosen reference lap. This function displays to the driver either a predicted lap time like "1:31.45", or a running difference time such as "- 0.34". The running difference works just like variance does, continually updating throughout the lap and starting at zero when the car crosses the lap beacon location. It reports the difference of the current lap being driven to the reference lap.

Split Times

Some systems will display a partial lap time, followed by the time difference of the current lap to the reference lap. This is called a *split time* and is very common on video games. Rather than continuously updating, they are updated at the split time locations, typically on straights when the driver has more time to read the dash display. Most tracks will have only three or four split times located around the track.

2.6 Data Alignment

Many different factors can cause misalignment in the overlay graph when comparing two different laps. Misalignment can be identified when the minimum speeds of each corner don't overlay on top of one another. In other words, the minimum cornering speeds which should happen at around the same distances, happen further apart. All of these issues are related to the distance calculation. The following examples will demonstrate four of the most common problems and how to solve them.

1. Graph is in time mode
2. Beacon transmitter was placed in a different spot
3. Speed calculation or tire circumference problem
4. Dramatic change in driving line around a corner

Below are two laps from Mid-Ohio correctly aligned. In the following examples, these same two laps are shown with various causes of misalignment.

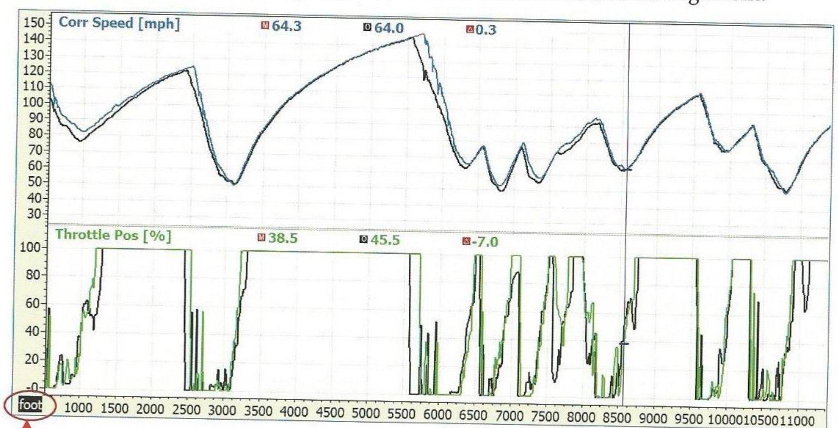


Figure 2.19 *Here are two laps showing all corners lined up, as judged by the minimum speeds in each corner.*

1. Graph is in time mode

If the x-axis is set to time, the data will be plotted based on time rather than distance. Traces appear aligned at the start of the lap, but gradually drift off further as the lap progresses. Such a graph would look like ***Figure 2.20***. This should be easy to identify and easy to fix,... as long as you remember to look in the bottom left corner where the units of the x-axis are labeled.

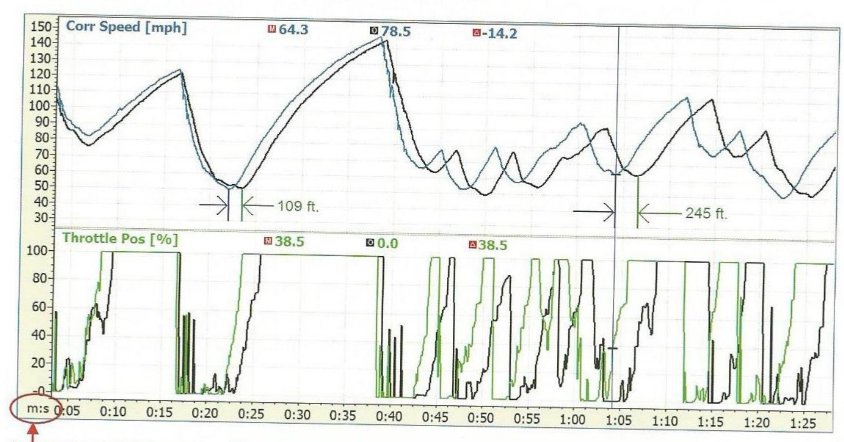


Figure 2.20 *When placed in time mode the same two laps show alignment problems which get worse with each corner.*

2. Beacon transmitter was placed in a different spot

If the traces appear to be shifted the same amount everywhere along the lap, then the lap beacon transmitter was probably installed in a different spot along the track. This can be fixed by applying a beacon offset to one of the laps. Always remember to place the beacon transmitter in exactly the same place every time!

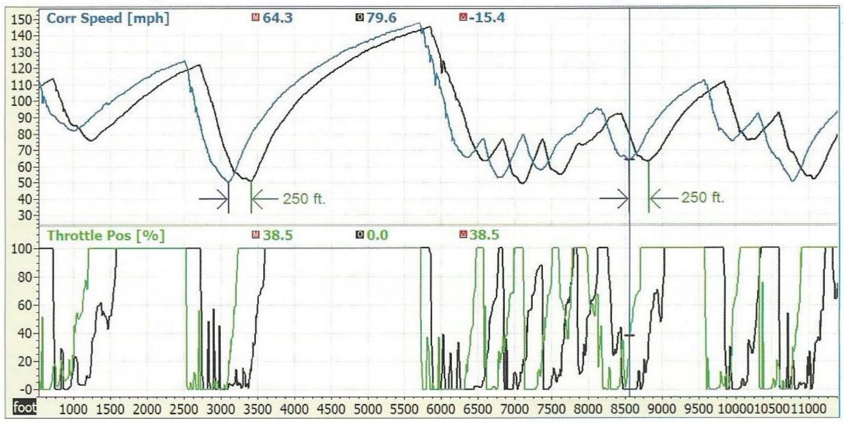


Figure 2.21 *The blue trace triggered off a beacon 250 feet after the black one.*

3. Speed calculation or tire circumference problem

If the traces start lined up but drift off throughout the lap, check for time mode first. Then check the actual lap distance of each lap separately. If speed or tire circumference was calibrated incorrectly on one of the laps, then the measured speed will be too high or too low. This creates a longer or shorter track distance. To correct for this problem, apply a scaling factor onto the speed channels, equal to the percentage difference in lap distances. Remember to correct the speed calibration in the data logger so the next data downloaded is correct.

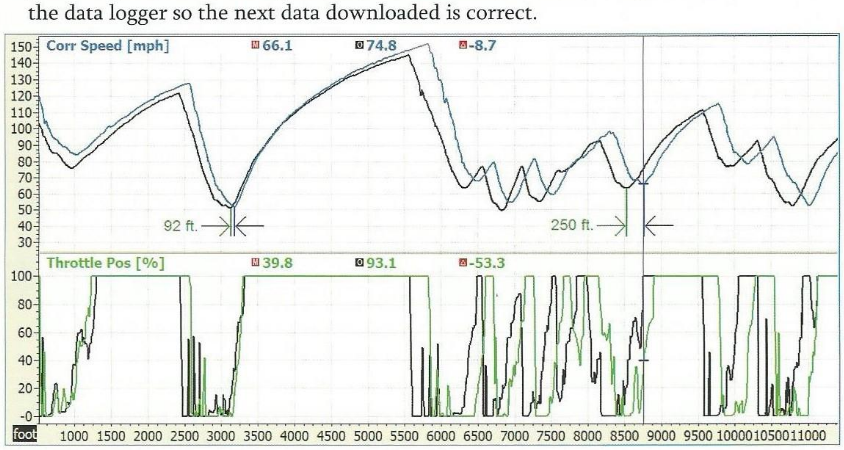


Figure 2.22 *The blue trace was calibrated with a tire circumference error of 3%. Even if one lap is faster, the distance should remain the same around each lap of the track.*

4. Dramatic change in driving line

If part of the lap appears to line up and then another part suddenly shifts, there was likely a change in the driving line which changed the lap distance. This is more difficult to identify and has no solution which fixes the entire lap.

Two laps from Road Atlanta are shown in ***Figure 2.23***. These are aligned during the first half of the lap, as verified by looking at the shape of the speed traces in each corner. But starting at Turn 6 through the end of the lap, the traces appear miss aligned. The amount of shift seems constant throughout the second half. The problem started before Turn 6. The speed trace is extended because the driver stayed on the throttle too long. The change in slope at the end of the braking zone shows the driver released the brake pressure to readjusted his line in an attempt to extend the braking zone without going off track. The driver over shot the corner and drove a longer distance around the corner. This creates the alignment offset due to a change in lap distance as the driven line was significantly longer.

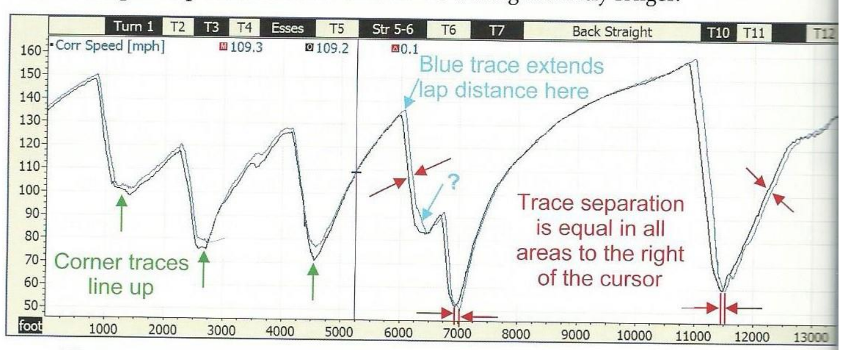


Figure 2.23 *Driver over-shoots braking zone for Turn 6. Traces no longer line up.*

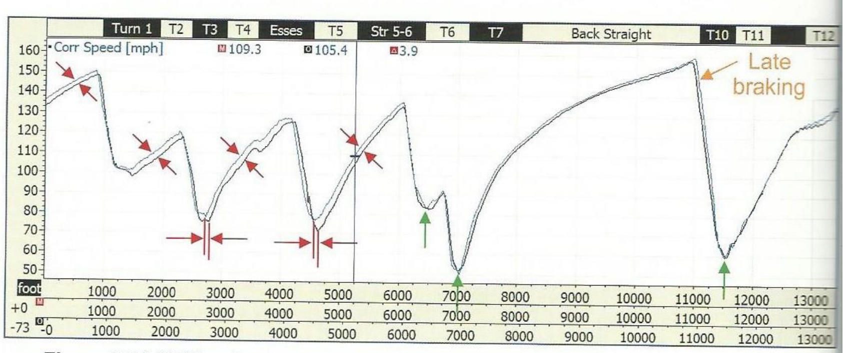


Figure 2.24 *Shifting the trace will line up the second half, but then the first half is off.*

In ***Figure 2.24*** the black trace is offset by 73 feet, such that the second half lines up and the first half does not. Now we can analyze the second half correctly. Notice the braking point for Turn 10? The speed trace is extended yet the speed trace in the curve still lines up. This is late braking done correctly!

2.7 Braking

The braking zone appears in the speed trace only because the driver must slow down for an approaching corner. It is defined as the section where the speed trace has a negative or downward slope. The braking zone will have two sections:

- Straight line braking: section of braking zone in a straight line where maximum stopping power is applied. This creates the steepest negative slopes in the speed trace.
- Trail braking: section of braking from turn in point until the brakes are fully released. Here the brakes are being released and the slope will be far less steep. This section can be long or short in terms of duration, depending on the corner and driving line.

The speed trace can be used to analyze four areas of braking performance:

- Braking Point; where the driver hits the brake pedal
- Braking Ability; how hard the driver is braking
- Braking Application; getting on the brakes
- Brake Lockups; how to judge wheel speed sensors for lockup

Braking Point

Having data that lines up correctly is extremely important when finding the distance between braking points for two laps. The braking point is when the speed trace changes from accelerating (climbing up / positive slope) to braking (falling / negative slope). The speed trace can provide a quick visual as to which driver is braking later. In the example below, the red trace obtained a slightly higher top speed by braking later than the black trace. It's not the short increase in speed generated by braking later that lowers the lap time, but the higher speed carried throughout the entire braking zone. This higher speed during the braking zone is also necessary when passing another car.

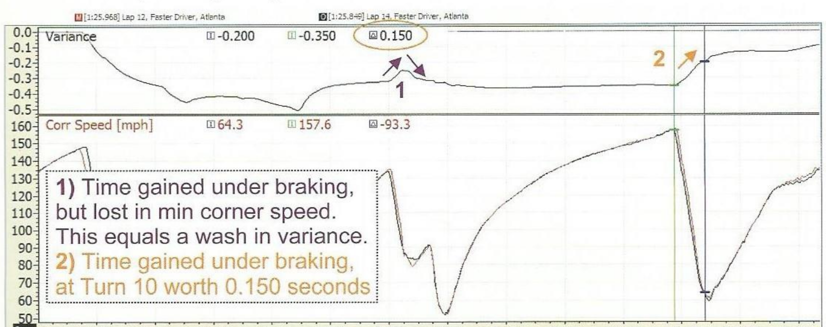


Figure 2.25 *The red trace braked later for Turn 10 at Road Atlanta.*

Zooming into the braking zone for Turn 10, generates the graph shown in ***Figure 2.26***. The analysis software can calculate the exact difference where the drivers began braking by placing cursors on the locations where speed first drops for each trace. Here the later braking was found to be 42 feet deeper. That might seem like a lot but when traveling 157 mph, 42 feet is only 0.18 seconds. About the time it takes to blink. And that was worth 0.150 seconds in lap time! It's not uncommon to see differences between braking points as high as 200 feet. The number is always higher than any driver would guess because they are traveling at high speeds where 200 feet looks like 20 feet.

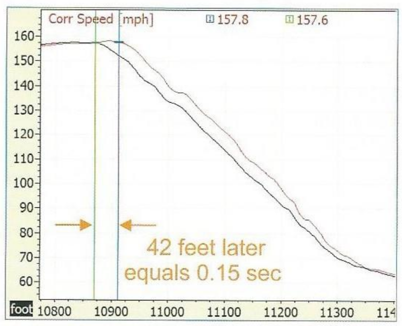


Figure 2.26 *Zooming in and using two cursors, the exact distance can be found.*

Note: Braking points will vary throughout the day or even within a session due to many factors. Some of these factors which should be remembered before making conclusions are:

- Lower vehicle weight improves braking ability. As fuel burns off so does the weight (20 gallons gasoline weighs approximately 120 pounds).
- Cold tires decrease traction, and therefore braking ability during the start of a session before tires warm up. Drivers must brake earlier.
- Conversely, cold tires also decrease the speed a vehicle can travel through the corner, lowering exit speed and speed down the straight allowing drivers to brake later.
- A driver that goes through a corner faster must brake earlier at the next corner because of higher straight speeds.

All of these things can be difficult for novices who will have to keep adjusting their braking points as their speed increases and they learn to brake better.

Sometimes getting a driver to brake later can force him or her to drive through the corner faster. As long as they have the talent to make it through the corner at higher speeds without crashing! Other times, braking later will scare the driver into over slowing for the corner. Such is the case in ***Figure 2.27***. The driver of the black trace brakes deeper into the corner, but over slows and not only does the minimum cornering speed suffer, so does the exit speed. Rather than maintaining a fast minimum speed with a bigger radius arc, the driver of the black trace squared off the corner with straight line braking, no trail braking and a tighter turning radius.

Figure 2.27 *Did the black trace over slow by accident, or was it caused by the late braking?*

Note: In qualifying, when a driver lays down a fast lap time the majority of speed gained comes from later braking!

Braking Effort

The negative slope or steepness of the speed trace is directly related to how effective the driver is braking, and almost always proportional to how much brake pressure is applied. A driver who maximizes the car's braking potential, will log a *steeper* decline in the speed trace and a lower lap time. In the example of ***Figure 2.28***, the red driver started braking later, but finishes at almost the same distance and speed for the corner. Using the variance trace, it can be easily seen that a little time was lost on the exit of the corner, but much larger gains were made while braking for the corner. One would expect higher brake pressures and higher G Forces acting on the car. The G Force Longitudinal channel will be examined later in this book with regards to braking ability.

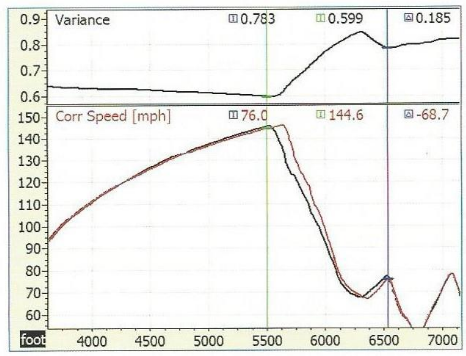


Figure 2.28 *Not only did the red trace brake later, more importantly broke harder!*

A more complex example shown in ***Figure 2.29*** yields these conclusions:

1. Braking begins at exactly the same point and with the same slope. Brake pressure would likely be the same.
2. The red car has less slope. This could be caused by wheel lockup, or perhaps the driver is lifting off the brakes when down shifting? Individual wheel speed traces would show any wheel lockups, while a study of the throttle trace would show the timing of throttle blips during down shifts.
3. Here the red trace has a steeper slope. Brake pressure should be higher on the red car.
4. Finally the slopes are similar again. Brake pressure is also likely to be similar.

Generally most cars can brake harder at higher speeds when there is more downforce and momentum. Speed, brake pressure and G Force Long will all correlate together.

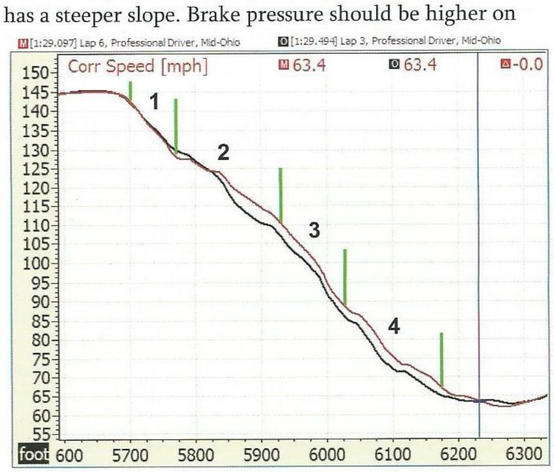


Figure 2.29 *In this complex example, the red trace has four regions of difference from the black trace.*

Braking Application

Some drivers ease onto the brakes while some slam on the brakes. Such behavior will show up in the shape of the speed trace where it transitions from accelerating to braking. The graph in ***Figure 2.30*** shows two braking zones. The black trace quickly switches from accelerating to braking in both, while the red trace has a smooth and slower transition into braking. The driver of the red trace had lost time on the straight leading up to the first corner, but by being smoother getting on and off the brakes the driver went through the corner faster and got a better exit. But in the second braking zone, the transition was way too slow and time was lost. Which method is faster depends on many things, all of which are car and driver specific. Things to consider are:

- Downforce; lots of it allow for quick and hard braking. As downforce falls off with speed, the amount of braking will decrease.
- Weight Transfer; the speed of weight transfer to the front is based mainly on the stiffness of the springs. Most racing cars have stiff suspension, so braking application can be quick.
- Brake Pressure Bias; the bias (pressure between the front and rear) is normally optimized for braking after all the weight has transferred. Therefore when first stepping on the pedal, too quick of an application might cause premature wheel lockup on the front. Adding in too much rear bias can make the application of brakes a very scary moment.
- Car Handling; being smooth helps keep the car happy and minimizes any undesirable added weight transfer from rotational momentum as the vehicle pitches forward. Being smooth is very important for fast corners.

As a general rule of thumb, a driver should push on the brakes as quickly as possible when in a straight line. Except for fast corners where smoothness can prevent upsetting the car's handling. A driver should be sampling the available traction by over braking and partially locking up the tires to know where the lockup point is.

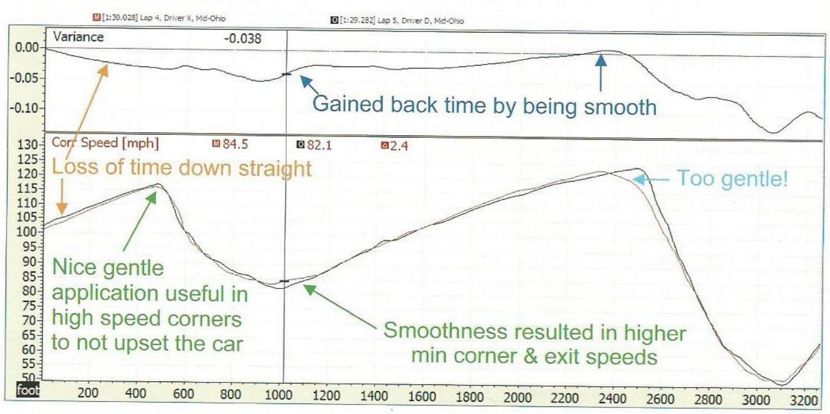


Figure 2.30 *Brake application is smoother for the driver of the red trace.*

Braking Lockups

As with any pair of objects in contact with one another, the static friction between them will always be higher than kinetic friction. Static refers to objects not moving relative to each other. Kinetic implies there is motion between them.

When a tire rolls along the ground, there is theoretically no relative motion between the surface of the tire and the ground. To maximize tire grip, tires should remain in static friction by rolling along the ground, as opposed to slipping which would result in kinetic friction. Luckily tires don't go from grip to slip instantly.

The transition of the tire contact patch from static friction to kinetic friction happens over time. Parts of the contact patch with the least amount of pressure will start to slide first, then more and more of it until all of the tire's contact patch is slipping and sliding. When cornering it is called *sliding*, when accelerating it is called *slip* and when braking it is called *lockup*.

Whenever a driver steps on the brake pedal too hard, one or more of the tires lockup. This can be found by looking at graphs of the individual wheel speed channels. Hence every car should have all four wheel speed sensors installed. The areas where the wheel speed trace falls below the true speed of the car is called a lockup. If the tire is still rolling, then it's called a *partial lockup*. As the lockup becomes more severe the speed difference increases until the point of *complete lockup*. This happens when the tire stops rolling and reaches a speed of zero. Usually followed by a puff of white smoke and the driver radioing into the pits wanting new tires!

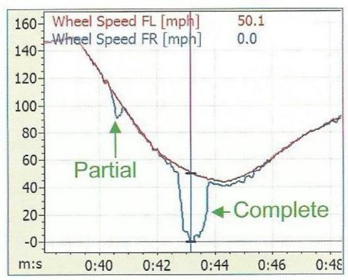


Figure 2.31 *Lockup types.*

With the pavement acting like sandpaper and the tire being dragged along it, a flat spot forms. These cause vibrations and becomes more susceptible to lockups every time the tire rolls back onto its flat spot. For maximum braking the speed difference should not exceed about 5%. Some amount of tire slip is necessary to generate the braking force, but anything beyond 10% slower is considered a lockup.

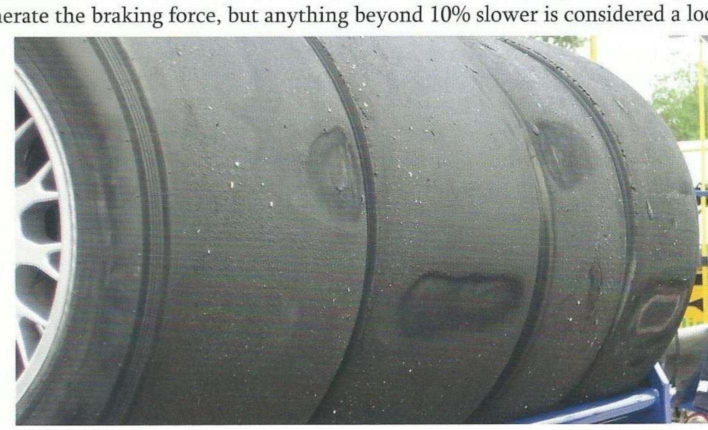


Figure 2.32: *Flat spots don't roll very well and are caused by lockups.*

Brake Bias

Weight transfers off the rear and onto the front during braking. Nowhere is this more evident than in a rental car when the front end dives down whenever the brake pedal is pressed. This weight transfer gives more traction to the front tires but less traction to the rear. Brake bias is a number representing how much braking pressure is applied to the front brakes compared to the rear brakes. If the front brake line had 560 PSI and the rear had 440 PSI of pressure, then the brake bias would be 56%. The bigger this number, the more front stopping power and the less rear stopping power. The actual number is not important, but the ability to adjust it can have a big impact on brake lockups.

A car with too much rear bias will lockup the rear tires first, and often result in the car spinning out of control. A car with too much front bias will lockup the front tires first, and simply push forward on its current path. No steering forces can be generated while the front tires are locked. Put another way, with more rear bias you don't see what you're going to hit, with more front bias you see what you're going to hit. Which one sounds safer to you?

Most racing cars have a brake bias adjusting knob that allows the driver to manually change the bias based on the car and track conditions. Brake pressure sensors are required to calculate the bias percentage number, but they aren't required to find the optimal bias setting. All you need are the four wheel speed sensors. The bias knob setting is adjusted based on the amount of front and rear traction available after weight transfer has occurred during braking. It should be set such that both front and rear wheels lockup at the same time.

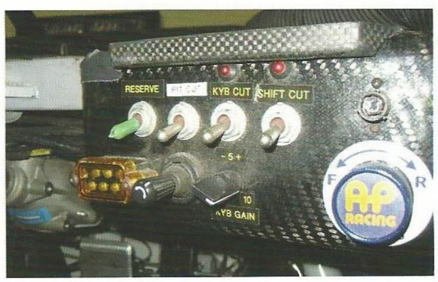


Figure 2.33: *The brake bias knob in the lower right is used to adjust how much pressure is directed to front brakes compared to the rear.*

△ Warning: This analysis should be done only during straight line braking, after weight transfer and before trail braking.

Laguna Seca is a unique track in that two of its heaviest braking zones are on hills. Turn 2 is downhill. This causes the rear tires to lock up because of the additional weight being shifted to the front due to the track inclination. More front bias would help. But going into the Corkscrew, the fronts crest over a hill before the rear and tend to lockup first. More rear bias would help. The fastest lap time will come from a brake bias which is a compromise of each braking zone.

Street cars don't have a brake bias knob. Newer cars rely on ABS to prevent lockups rather than relying on driver talent!

Note: Don't assume measured brake bias will be constant. Brake bias can change during the application or release of pressure as it torques the system in different ways. Friction and volume of fluid movement also plays a role.

Braking – Straight Line Lockups

It will always be during straight line braking where the highest brake pressures get logged and the slope of the speed trace decreases the most. In ***Figure 2.34***, there is too much rear bias. Notice there is no lockup on the initial brake application for either the front or rear, but shortly thereafter the rear wheels continually lockup until the start of trail braking. Most drivers prefer a slight front bias as rear lockup makes the car nervous and loose, which is not desirable when attempting to pass another car.

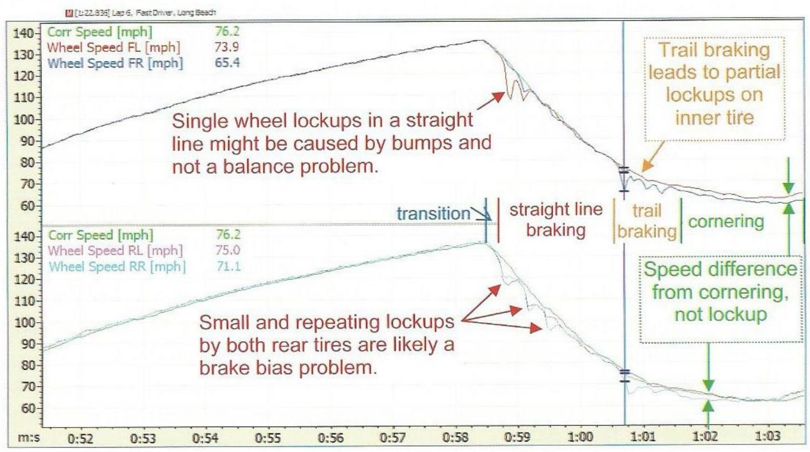


Figure 2.34 *Brake lockups on the back straight heading into a right hand corner on the Long Beach Grand Prix circuit.*

△ Warning: Always look for both wheels to lockup before making a conclusion that the brake bias is set wrong. Don't get confused by seeing a single wheel lockup. In the example above the front lockup is caused by a bump, which is common for street circuits like Long Beach.

The differential ties the two driven wheels together and can have an effect on braking. To prevent lockups from bumps, more stability can be gained by a differential that doesn't allow slip from side to side while braking.

Braking – Trail Braking Lockup

Trail braking is when a driver is steering while still on the brakes. With even the smallest amounts of trail braking, weight gets transfer from side to side. Because there is less weight on the inner tire, it will lockup more often. Trail braking lockups have less likeliness to flat spot because the tire is unloaded. Small lockups and most trail braking lockups are less important to worry about.

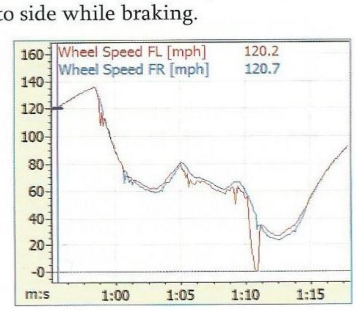


Figure 2.35 *Complete lockup while trail braking.*

If partial lockups aren't present anywhere in the data, then it might be time for some additional driver training. This is a clear sign that a driver is not maximizing the braking potential in the race car. Drivers should sample the traction while braking. By achieving small amounts of partial lockup, a driver can find the maximum braking capacity in every corner without damaging the tires. But this takes skill. Skill that is easily done by a computer.

Braking with ABS

All newer passenger cars use some form of Anti-lock Braking System called ABS for short. Under heavy braking which would normally lockup the tires and prevent steering control, a computer takes over to keep the tires rolling. The ABS computer controls the brake pressure at each corner of the car. Maximum braking can then be achieved by sensing when the tire starts to lockup and releasing brake pressure from that tire to keep it rolling.

For racing cars, ABS is much like traction control only in reverse. While it can not improve the physical grip level of a tire, it can make braking at the maximum level much easier for the driver. Racing style ABS computers are tuned differently from street car units. Street car versions aren't programmed to handle the higher grip levels of racing tires and their corresponding grip curves which define the tire slip. Notice in ***Figure 2.36*** how ABS allows for maximum braking efficiency by not letting the lockups get too large. Not only does it help in straight line braking, but ABS also assists the inner tire lockup when trail braking.

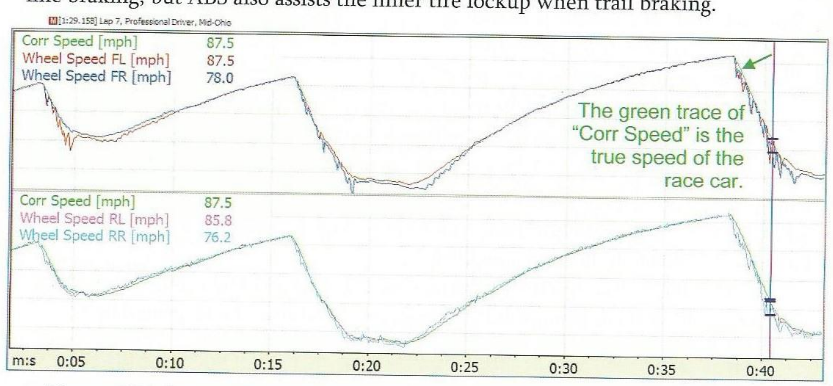


Figure 2.36 *Great example of ABS controlling wheel lockup in each braking zone.*

When driving a car with ABS, optimal performance is achieved with a quick application of braking force. Then when ABS activates, the driver should not remove foot pressure off the pedal! Rather maintain a steady force up to the corner turn in point. Many novice drivers will release pressure at the point of ABS intervention, which only hurts its performance.

Note: Always compare every braking zone for consistency before making conclusions about brake bias setting. Many things change the ideal bias from one corner to another; trail braking, downforce changes from speed, hills and bumps. A compromise of all these things are needed to obtain the lowest lap time.

2.8 Wheel Slip

When a driven tire loses traction the speed trace shoots up, and when the tire regains traction it decreases back down to the true vehicle speed. This is called wheel slip and it appears like the opposite of brake lockup.

In fact any amount of acceleration will cause some amount of wheel slip to be measured. Just like while cornering where the tire exhibits a cornering slip angle with any amount of turning forces, the same happens during acceleration creating longitudinal tire slip. Only when the car is at a constant speed, neither accelerating or braking will there be zero longitudinal slip.

Combined with the slip from acceleration is the increase in speed due to a tire circumference change. When a rotating torque is applied to the tire, its vertical stiffness drops which effectively lowers the stiffness of the sidewall. The applied torque also compresses the front side of the contact patch, resulting in less rolling circumference. A smaller rolling circumference increases the measured wheel speed. And any wheel speed sensor noise is added into the mix as well.

The equation below calculates the percentage of forward slip the rear tires have compared to the front:

Wheel Slip % = Fastest Front Wheel Speed / Fastest Rear Wheel Speed x 100

There are times when the wheel slip equation won't use the fastest rear wheel speed. Instead it might use the slowest wheel or an average of both. This might be beneficial when using the wheel slip calculation for traction control and no engine power cut is desired for single wheel slip. The best balance number will depend on the differential being used, the balance of the car and driver's preference.

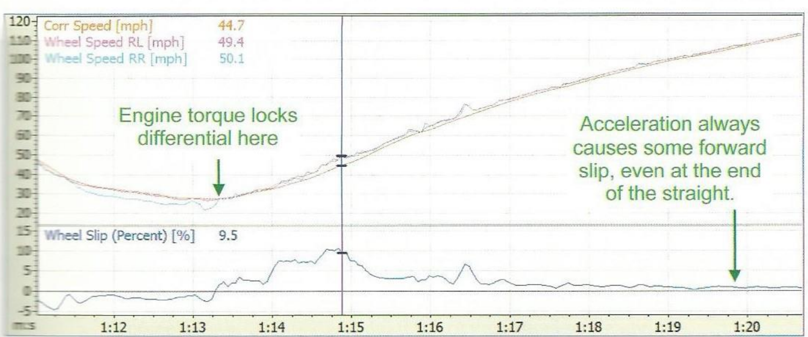


Figure 2.37 Wheel slip accelerating out of a corner. Notice in the middle of the corner how the wheel speeds deviate due to corner radii differences between the left and right sides. Corr Speed in orange is the fastest of the front rolling tires.

Traction Problems

Identical to the front tires, when going around a corner the inside rear tire should turn at a slower rate than the outside tire. Unlike the front tires, both driven tires are connected together through a differential. Many types of differentials are available, and each one has an impact on the left and right wheel speed relationship when cornering or accelerating.

Open Diff

An open differential will allow the tires to spin completely independently from one another. Like the front tires, in a corner the inner wheel rolls slower than the outer. This type of diff absorbs the least amount of power as both tires won't be fighting each other. The downside occurs if one of the tires loses traction, the engine's power is transferred to that tire and acceleration out of the corner is compromised. The open diff is simple and inexpensive. In the graphs below, the graph on the left has an open diff. Notice how the speeds have separated going into the corner and how coming out a single tire is free to spin.

Locked Diff

A locked differential will always force both tires to spin exactly the same speed at all times. In this case, there is forced tire slip on both tires as they negotiate around a corner. The inner tire is sped up while the outer tire is slowed down. This can rob horsepower and was typically used only in very high horsepower cars such as the old CamAm series of the 1970's. Very few race cars use this type of diff today. Instead they use a modified version where the diff is open when no power is applied (such as when braking and turning) but locks when power is applied. This type of diff creates a trace shown on the right graph where both rear tires accelerate together out of the corner.

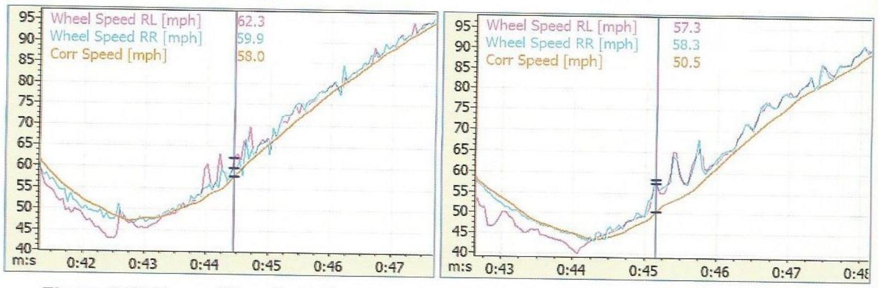


Figure 2.38 *Open diff on the left versus locked diff on the right. Compare how the wheel speeds move in relation to each other when they start slipping.*

Limited Slip Diff

In between the open and locked diff is a limited slip differential. The limited slip diff can be adjusted to change when and how much force the tires share. Some are mechanically controlled via friction plates while others are fluid or hydraulic controlled. This might seem to be the ultimate solution but can be expensive and require more maintenance.

Ramp angles are used to change the percentage of torque between the wheels, and a preload adjustment locks the diff until that amount of load between the two driven tires is reached. The adjustable diff could also have different locking percentages when on or off the throttle. These adjustments can be used to change the handling of the car (oversteer or understeer). Tightening the diff will create more understeer, loosening the diff creates less understeer. The diff should be adjusted to prevent traction problems. For more traction the limited slip differential can be tightened. But then the cornering ability could suffer as cars tend to push with a tighter adjustment. There will be an optimal balance for traction, and any change from that is used as a last resort to cure handling issues. Below is a graph that shows how the rear tires act like an open diff or locked diff depending on the situation.

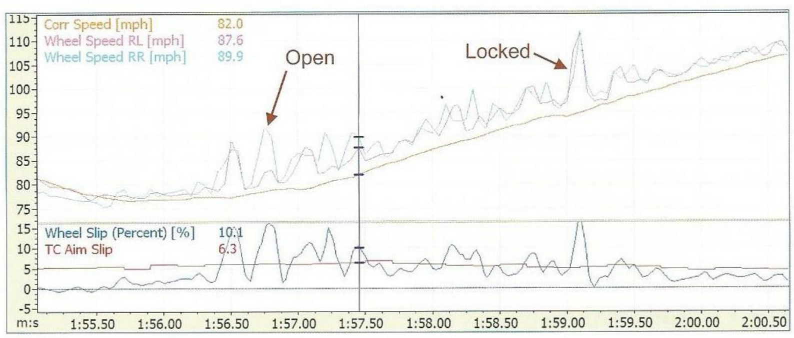


Figure 2.39 *On this bumpy Sebring track with a limited slip diff, the rear wheel speeds exhibit everything from full open to full lock.*

In ***Figure 2.40*** below, the wheel slip trace is shown with traction control aim slip added to the graph. This trace is the goal of a traction control system, where any wheel slip above this amount causes traction control to activate.

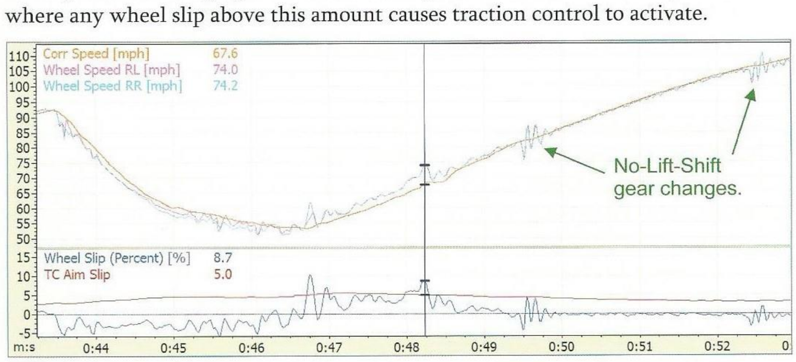


Figure 2.40 *Quick gear changes cause the rear wheel speeds to jump around especially when measured off the inner CV joint instead of the outer. It's important to make sure these jumps don't cause traction control to activate.*

2.9 Cornering Speeds

A corner or turn is any section of the race track where steering angle is changing the direction a car is traveling. A corner can be broken down into three parts:

- Corner Entry: from the start of steering wheel movement until maximum steering angle is reached.
- Mid Corner: where no braking or accelerating takes place, and all of the available tire grip is being used for cornering.
- Corner Exit: from the start of acceleration with a release of steering.

Many other specific locations are of interest when analyzing a corner, including:

- Top Speed: maximum speed down a straight, usually right before braking.
- Braking Point: location where driver begins to apply the braking.
- Turn In Point: location where driver begins to turn the steering wheel.
- Entry Speed: speed at which the driver enters the corner, at the turn in point.
- Minimum Cornering Speed: lowest speed throughout a corner.
- Apex: location where the car is closest to the inside edge of a corner.
- Full Throttle Point: the location where throttle reaches maximum.
- Exit Speed: speed when full throttle is reached or steering returns to straight.

Driving Line Analysis

A "driving line" or "racing line" is an imaginary line that follows the center of the vehicle around the race track. It maps the path of the race car, and can be shown with GPS positional data. Driving lines vary based on the track layout, car design, and a driver's style. A quick review of the three basic types of driving lines:

Type A) Slow in, Fast Out: If a long straight follows after the corner, then speed down the straight is more important than speed through the corner. Comprised mostly of straight line braking with little to no trail braking and a late turn in point. The tighter radius of curvature forces a slower minimum speed, yet allows for a quicker transition from braking to accelerating with little to no neutral throttle. Full throttle can be reached sooner and likely by the apex. In order for this to be faster, the straight must be long enough for the speed gained to offset the speed lost in the corner.

Type B) Textbook Line: If the corner does not precede a long straight or is considered fast (high speed), then the minimum cornering speed becomes the most important factor. Some straight line braking is followed by plenty of trail braking to maximize all of the available tire grip. A turn in point is chosen which creates the largest possible radius through the corner. With the least amount of steering input it has the fastest possible speed through the corner.

Type C) Fast in, slow out: The least commonly driven and often only as a last resort. Used when a driver enters a corner way too fast by mistake. While crazy late braking can be faster entering the corner, both mid corner and exit speed will suffer. In order to extend the length of straight line braking, a small turn is made early, giving a straight path past an early apex. This leaves the driver with a very late turn in point and no mid corner to speak of. A very slow and tight turning radius, helps the driver to reach full throttle immediately with the release of all steering wheel input.

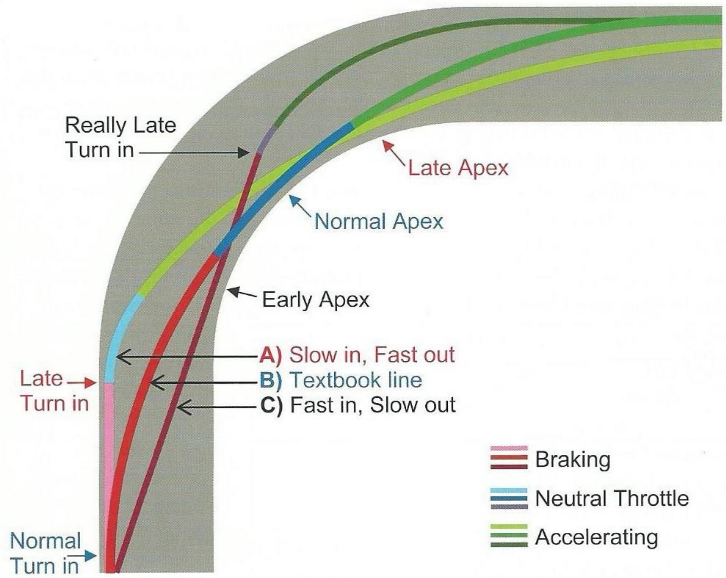


***Figure 2.41** Different cornering lines are driven based on the configuration of the track both before and after the corner.*

Note: Low horsepower racing cars can reach full throttle earlier in the corner exit. High horsepower racing cars may not reached full throttle until very late in the exit.

△ Warning: *As long as the driver is at or near the limit of the race car, the shape of the speed trace can be used to estimate the driving line.* See the examples below. If the driver is not at the maximum and driving much slower than the limit of the car's ability, then conclusions about the driving line cannot be made from speed alone. Steering and G Force Lat will be required.

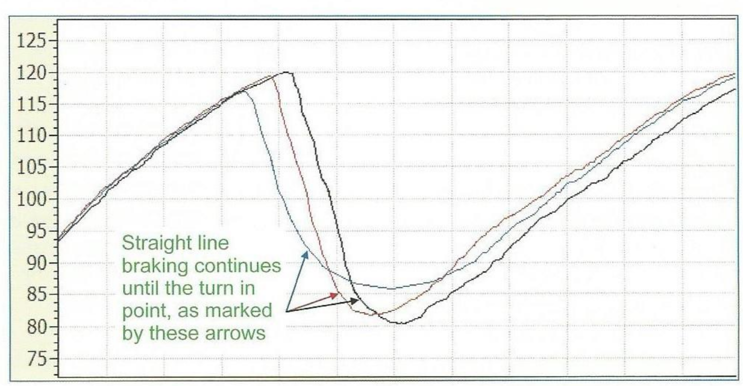


***Figure 2.42** Speed traces for the three types of driving lines.*

Minimum Corner Speed

Is the old saying "slow in, fast out is quicker than fast in, slow out" always right? Is a higher minimum corner speed quicker? Is trail braking faster? With the help of data acquisition all of these questions can now be answered, and all by looking at a single channel called speed. Now you can determine which corner a theory applies to and which corners it doesn't.

The following three graphs are from Turn 1 at Mid-Ohio, a medium to high speed corner. Here, different lines may result in exactly the same lap time. In ***Figure 2.43***, a Type B and Type C ended up even. The gains made from late braking in the black trace were offset by the higher minimum and exit speeds of the blue trace. Late braking often leads to slowing down more than what is necessary as a driver gets spooked by the faster entry speed into a corner.

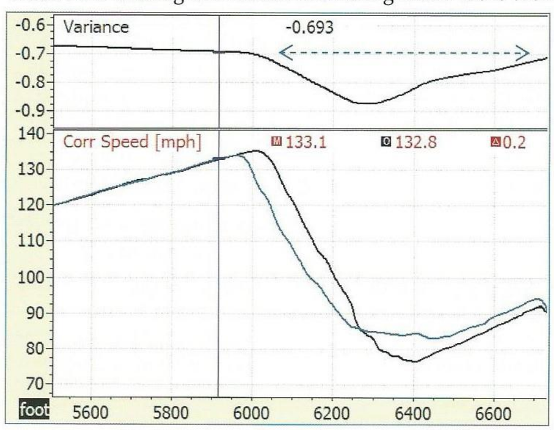


Figure 2.43 *In this corner, the variance evens out between cornering line styles B & C.*

The classic, "slow in, fast out" comparison is shown in ***Figure 2.44***. By the middle of the corner Type A in red is slower by 0.10 seconds. However, the earlier acceleration of the red trace allows it to make up 0.23 seconds for a net gain of 0.13 seconds after the straight. Note the minimum cornering speeds are very similar. If the blue trace was a true Type B, then it should have had a higher minimum speed than Type A. Perhaps the blue trace slowed more than it needed to? Perhaps the blue trace should have started braking earlier to not be so rushed during trail braking making it easier to maintain a higher speed through the corner?

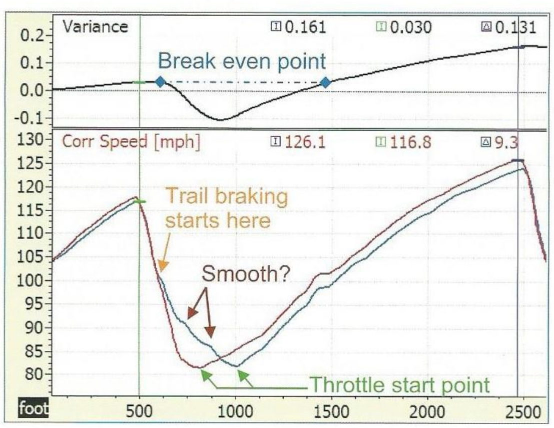


Figure 2.44 *The red trace, Type A line is faster out of turn 1 at Mid-Ohio than Type C. The black trace, Type C should have had a deeper braking point.*

In ***Figure 2.45***, the traces again show that both braking points happen at the same spot. This time the driver of the blue trace achieved a faster minimum speed compared to the same red trace as before. This higher minimum speed gains the driver 0.11 seconds. And even though the red trace got on the throttle earlier, the exit speeds are the same. In this example the blue driver displays more smoothness with the controls and manages to extract maximum speed out of the car as a result.

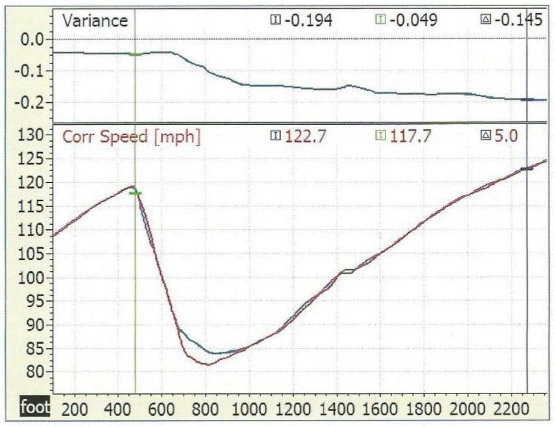


Figure 2.45 *The red trace attempts the Type A line, but didn't brake any later and didn't exit the corner with more speed than the Type B line. The driver of the red trace was not on an ideal racing line, or wasn't at or near the limit of the tires.*

In ***Figure 2.44***, the blue driver simply entered the corner too fast. Some caused by braking later equal to the Type A driving line, but more importantly releasing the brake pedal too early and trying to trail brake too much and too soon.

All corners have different characteristics affecting which is the quickest driving line. There are infinite possibilities of driving lines when these three different types are combined together. Which line is best depends on every aspect of the track, the car, and the driver. Drivers should concentrate on fast corners first, since the largest amount of time can be found in those. They are what separate the quick driver from the slow driver, the professional from the amateur, and the men from the boys.

Note: When experimenting with different lines, always spend at least three laps or half the session driving one line before switching to a different line. Mixing more than 2 lines in a single session makes it difficult to keep track of. Also, comparing only one lap tells nothing about repeatability. Having multiple laps of each line will allow the variance result to be averaged, and help draw a more solid proven conclusion.

2.10 Straight Line Speed

It seems appropriate to put this section after cornering. That's because the speed down a straight is mostly dependant on the speed exiting the prior corner. When comparing speed traces down a straight, any differences in speed might be caused by many different factors which include:

- Exit speed off the last corner?
- Being in the wrong gear coming out of a corner?
- Different gear ratios?
- Slow or problematic gear changes?
- Drafting another car which increases speed?
- Traffic slowing the car down by getting in the way?
- Engine power is different due to air temperature, barometric pressure, air/fuel mixture or any other engine parameter?
- Is the speed or tire calibration correct?

Some drivers are always asking how fast did I go? Sorry… but in road racing top speed rarely correlates to the lowest lap time. In fact most engineers don't even notice the top speed when analyzing data, unless they are studying aerodynamic changes. An interesting exercise for any track is to compare the top speeds between all of the laps. Generally the highest top speed will occur on a slower lap.

		Slower Driver, Road Atlanta						
		Lap 1 [1:28.835]	Lap 2 [1:27.723]	Lap 3 [1:27.064]	Lap 4 [1:26.790]	Lap 5 [1:26.955]	Lap 6 [1:31.552]	Lap 7 [1:26.870]
Corr Speed [mph]	Max	157.5	159.1	159.0	159.3	159.6	158.8	158.6
Throttle Pos [%]	Avg	65.4	67.2	68.1	70.0	69.3	57.7	68.0
Brake Time Lap [s]	Max	15.75	14.17	13.95	13.35	12.71	16.56	13.54

Table 2.1 *Channel Report showing how Lap 5 had a higher top speed, and less time spent under braking. Yet Lap 4 was faster.*

Analyzing Aero Changes

Comparing top speed and more importantly the slope of the speed trace can shed light on aerodynamic changes made to the car. This must be done following these rules to insure the comparisons are apple to apple:

- only on the same straight of the same track
- with the same gear ratios
- with no draft or traffic
- same vehicle weight and/or fuel load
- same outside air temp, barometric pressure and other engine parameters

It can then be said that a car which accelerates faster and has a higher top speed will have either less aerodynamic drag or more horsepower. The increase in speed should be a smooth and continuous increase all the way down the straight.

△ *Warning:* Remember to compare multiple laps before making conclusions. Any variations on a lap should void that data from analysis. The effects of any aero changes will be the same on every lap, so compare more than one.

Note: Due to its steeper slope, analyzing the Engine RPM channel might yield clearer results. This is discussed in the Engine RPM chapter.

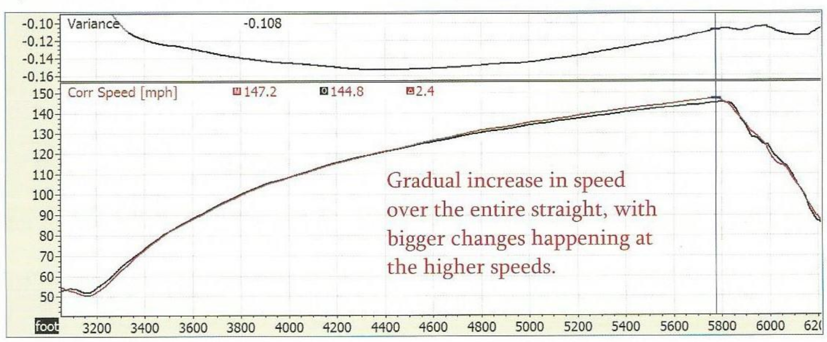


Figure 2.46 *Less wing angle coming out of Turn 2 at Mid-Ohio. Notice the earlier braking point due to the higher top speed.*

In the example above, the red trace comes out of the corner a tad slower than the black trace. Gradually over the entire straight the red trace picks up speed to become faster than the black trace. Knowing what changes were made between sessions is imperative. Without feedback from the driver or in-car video, it can be difficult to know with certainty if drafting was the cause of such speed increase.

Chapter 3 RPM

The most important channel for engine builders is one that looks like a bunch of saw tooth peaks. Each rise between the peaks correspond to the acceleration through each gear. During acceleration, the RPM rise is much taller and quicker in lower gears, becoming slower and more flat in higher gears. Lower gears (higher gear ratios) allow for more torque to reach the tires, but the maximum speed in that gear is less. Higher gears (lower gear ratios) allow for more speed but the lower torque equates to slower acceleration. Also, the faster a car goes the more aerodynamic force the engine must overcome to accelerate. Eventually the torque through its higher gears isn't enough to accelerate and the car reaches maximum terminal speed. Down shifts appear as the opposite with downward slopes in very short durations between each peak.

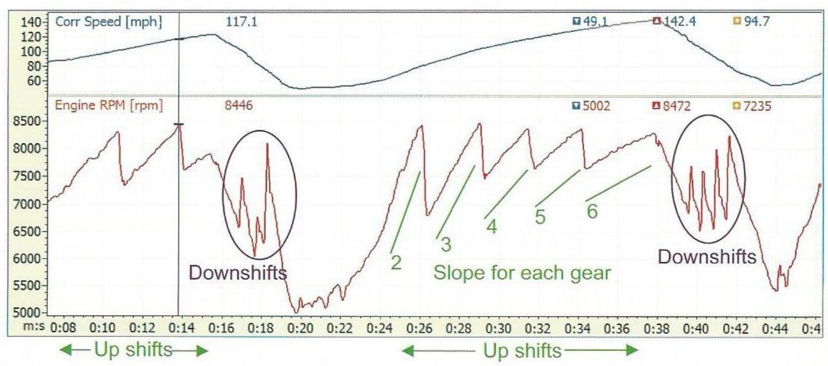


Figure 3.1 *Graph of Engine RPM. For each up shift the gear ratio decreases and aero drag increases. Therefore each higher gear has less slope and accelerates slower.*

The graph in ***Figure 3.2*** details a sequence of events as follows:

1:30 - Car comes into pit lane and stops according to the speed trace.

1:35 - Engine is turned off.

1:45 - Logging stops and is started again after some time period. This creates a discontinuity seen in the temperature channel. How much time went by is unknown because there was no logging active to record this time. The engine is started again which likely initiated logging to restart.

1:55 - Driver takes off down pit lane, verified in the speed trace.

2:15 - Driver turns off the engine and coasts a short distance before stopping again, likely at the end of pit lane waiting to be released out onto the race track by a track marshal.

2:30 - Engine is restarted and idles for about 40 seconds.

3:10 - Car takes off and speeds away.

Notice how the heat soak builds up in the temperature sensor after the engine is restarted the second time around the 2 min 30 sec mark. Heat soak is the release of heat from the engine while the car is stopped. This temperature would have otherwise been released into the atmosphere from the air flowing through its radiator. With the engine stopped, the coolant sits in the passages of the engine block gathering heat from the cylinders. Then when the engine is restarted, this hotter coolant flows by the engine temperature sensor and that causes the trace to climb up over 200° F. After the heat soaked coolant passes by the sensor, this temporary increase drops to a more stable temperature at idle. The engine is still running hot because there is no air flowing through the radiator. Once the car is in motion down the track, it cools more than 30 degrees. There was no discontinuity here as the trace is nicely curved, compared to the earlier restart at 1 min 40 sec.

Engine builders are most concerned with the running temperatures on track rather than the absolute maximum which is often influenced by heat soak.

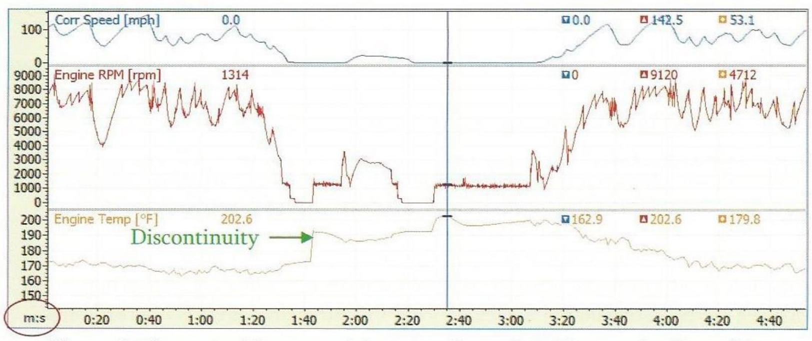


Figure 3.2 *A graph of the same data, only with x-axis in Time mode. Now all the data appears even when the car is not moving and speed is zero.*

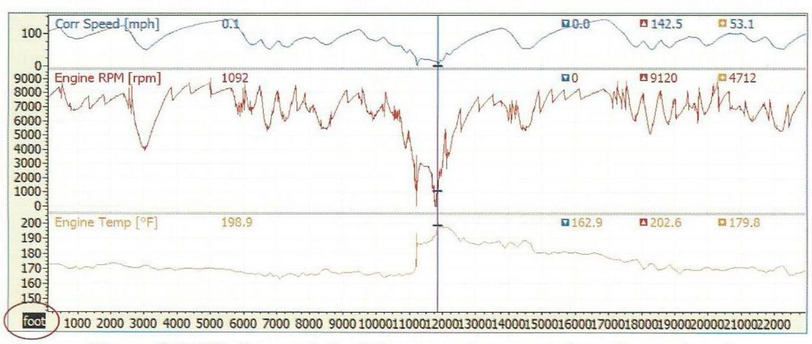


Figure 3.3 *With the x-axis in distance mode, areas where the car is not moving simply disappear.*

☑ Check: When comparing different laps the x-axis should always be in distance mode. But when looking at engine related channels, the x-axis is better suited to time mode.

Traction Problems

Because the rear wheels are connected to the engine through a clutch, traction problems also appear in the RPM trace. Below is a graph that displays traction problems very clearly. The engine spins higher as if the car is moving faster than it really is, identical to the wheel speed traces during wheel slip.

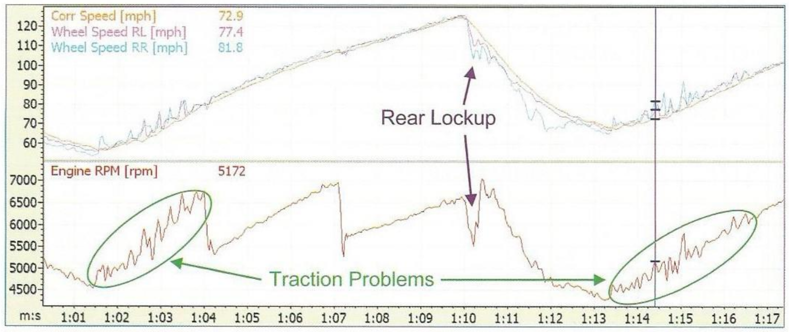


Figure 3.4 *The RPM trace looks much like the rear wheel speeds when the engine overcomes available traction. Notice the traction problems go away after shifting into a higher gear, due to the differences in gear ratio.*

There is one exception that can cause engine RPM to spike up when traction is not a problem, and that is clutch slip. While clutch slippage is important in drag racing, it should not normally occur in road racing. If the RPM trace slips upward and it looks like a traction problem, verify it with the wheel speed traces before drawing a conclusion. If the wheel speed traces don't show the increase but RPM does, then perhaps it was in fact clutch slip.

Any rear wheel lockup should also be noticed in the engine RPM trace, providing the clutch isn't open. Lockups can be a common appearance during down shifts. And if the driver is using the clutch then it is possible for them not to appear in the engine RPM trace.

Straight Line Performance

Compared to a speed trace, smaller variations in speed can be identified more easily in a RPM trace due to the steeper slopes. When looking at straight line performance for comparing engine power or aerodynamic loads, adding a engine RPM trace will be very helpful.

Note: Remember when comparing such slopes, they are only valid if the gear ratio is the same. Be aware of traffic, drafting and engine parameters also.

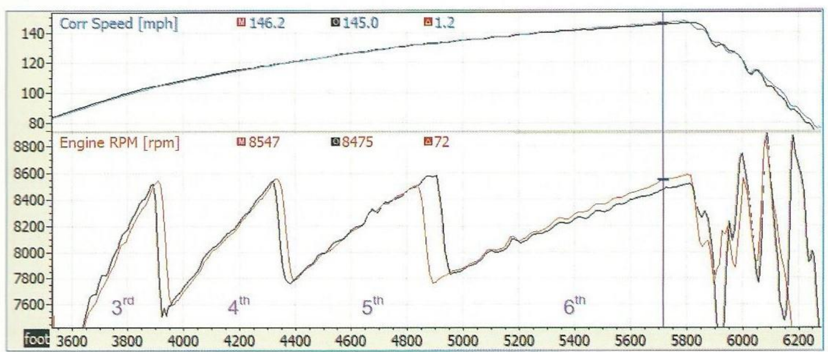


***Figure 3.5** Was this speed increase due to more engine power, lower rear wing, gear ratio change or drafting?*

In ***Figure 3.5***, notice at the cursor how there is a speed difference of only 1.2 mph but an engine difference of 72 RPM. The steeper slope amplifies differences. The ultimate question is what caused this speed difference?

More engine power? In both gears 3rd and 4th there seems to be no difference in acceleration. If the engine power was greater for the red trace then it would also show in the lower gears.

Lower rear wing angle? While this improves aerodynamics at any speed, the percentage of effect is greater at higher speeds. This is a plausible explanation. But if so, there should have been more of an increase in the 5th gear slope, yet there is not. All the change in speed occurs in 6th gear. Luckily rear wing angle should be recorded on the setup sheet.

Gear ratio change? Gears 3rd and 4th show no difference. While 5th gear shows a very small difference (ignoring the earlier shifting point of the red trace), 6th gear is quite different. Luckily this conclusion doesn't require guessing as the gear ratios should also be recorded on the setup sheet.

Drafting another car? This conclusion makes the most sense for the graph above. It would be safe to say the draft started about half way in 5th gear, as this is where the RPM lines start to change in slope. In 6th gear the slope difference changes a lot as the cars get closer together. The early shift into 6th is common for a driver drafting, but not pulling out to pass. It also saves fuel.

An additional check would be to compare multiple laps. The prior three conclusions would show the same results on every lap whereas drafting would not.

3.1 Over Revs

Any time the engine RPM goes over a limit determined by the engine builder it is called an over rev. Often the number of over revs combined with the maximum RPM of each over rev will help determine the amount of damage done to the engine. The engine part which causes this limit could be a stretched rod, broken valve spring or any number of internal parts. Sometimes the racing series will mandate a lower rev limit than the parts can handle, in order to control power levels between manufacturers or engine sizes. Always check with the engine builder to know what the real RPM limit of the engine is before damage occurs. With the RPM trace, both the number and amount of over revs can be found.

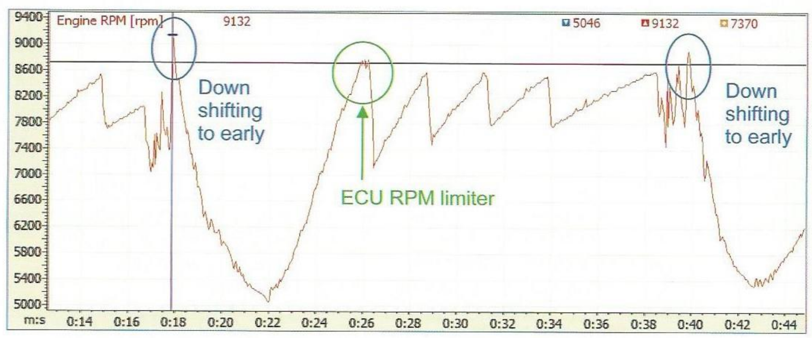


Figure 3.6 *Graph showing three over revs.*

When viewing RPM data, it can be handy to put a horizontal line across the graph corresponding to where the RPM limit is. Then a quick and easy look can spot each over rev and how close to the rev limit each shift was made. Another useful feature is to use the software's maximum value finder. In this example the upper right corner will list the minimum, maximum and average RPM for the data shown in the graph. Using the mouse cursor and clicking this value can move the cursor to that location.

ECU Rev Limiting

Most newer race cars use some form of rev limiting to prevent accidental over revs by drivers who forget to shift. The ECU or engine control unit reduces power of the engine by cutting out the fuel injection, ignition of spark plugs or in extreme cases by closing the throttle in drive-by-wire cars. Every car is different in regards to its RPM limit setting and its control method. For soft cuts it might not be harmful to keep driving with the throttle down while on the limiter. But for most cars, the limiter will slow the car down too much and lap times will suffer. In ***Figure 3.6*** the green circled over rev was caused by the driver forgetting to shift. The throttle was down all the way and the ECU cut engine power to prevent it from increasing any higher. The ECU however cannot prevent mechanical over revs which are common during down shifting and shown with blue circles above.

Note: If the car is geared incorrectly, a driver might activate the rev limiter near the end of the straight. If the length of time on the rev limiter is three seconds, the driver might come into the pits and claim they are losing three seconds on their lap time. This is not true. Remaining on even a harsh rev limiter for three seconds would not account for more than a few tenths of a second in lap time. An easy way to measure this is to compare with a properly geared lap and see the variance trace for how much time is lost while on the rev limiter.

3.2 Down Shifts

The ECU rev limiter works great for drivers whom forget to shift. However, it cannot prevent all over revs. For most race cars there is no method to prevent over revs while down shifting. These are called mechanical over revs because they are forced through the gear box into the engine. It happens when a driver rushes their down shift by putting the car into a lower gear sooner than it should be. It creates a spike in engine RPM which exceeds the limit of the engine.

Done correctly, down shifts will not disturb the balance of the car while braking. But if done too early, the down shift can contribute to rear tire lock up and potentially sending the car into a spin. Because the down shifting technique is dependant on the correct amount of throttle, it will be discussed in the chapter of throttle, where both throttle and engine RPM will be used for analysis.

In the two examples below, the left graph shows a nice controlled down shift technique. Those drivers who are skilled and patient with down shifts create a very consistent pattern. In contrast, some drivers aren't very consistent. The down shifts get rushed, leading to over revs and inconsistency as seen on the right graph. The graph on the left is much easier on the engine and gearbox, while the one on the right can contribute to early failures.

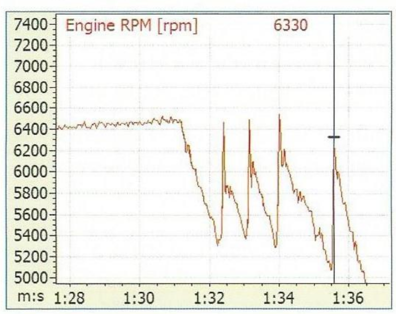


Figure 3.7 *Good consistent downshifts.*

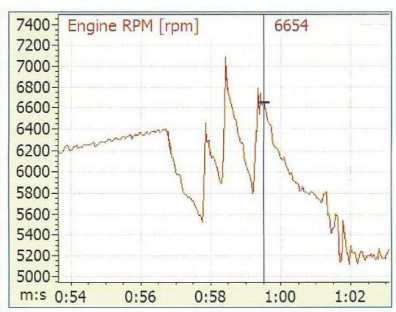


Figure 3.8 *Inconsistent and rushed.*

Some advanced race cars use a down shift blocker. It is a mechanical lock on the shift mechanism which won't allow the driver to down shift into the next lower gear until the car's speed drops low enough. It requires tire circumference and gear ratios to be input into the ECU for control. Very few cars have such a system, so the driver is free to mechanically down shift at will in most race cars.

3.3 X-Y Plot of RPM vs. Speed

Computer programs are available to help an engineer see what speeds different gear ratios allow for. They present this information in a X-Y plot of RPM versus speed. Such a plot can also be created from logged data. Speed is located on the x-axis with RPM on the y-axis. Each data point is plotted at its speed and its RPM at that moment in time. The bands created represent the RPM rise through each gear. As plot moves from left to right during acceleration each up shift drops the RPM into the next band.

The plot can be viewed from one laps worth of data or an entire session. In the plot below, different colors represent varying amounts of throttle position. From the legend, color is varied from orange at 0% to blue at 100%.

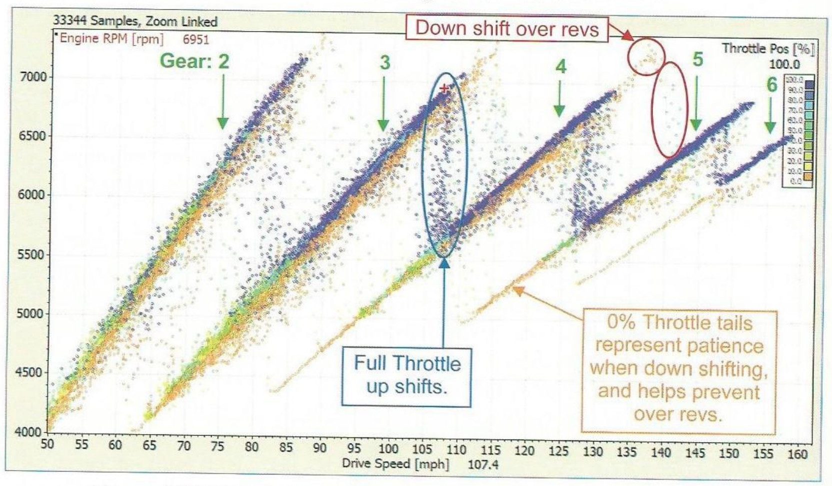


Figure 3.9 *X-Y Plot of Speed versus RPM for 5 laps of data at Sebring.*

Ideally there should be no overlap while at full throttle. However, there will always be some amount of overlap, equal to the variance in timing each up shift, but wide ranges of overlap might indicate lost time. Overlaps are the sections where a driver could have been in a lower gear providing faster acceleration.

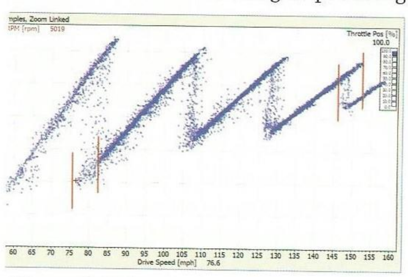


Figure 3.10 *Overlap at 100% throttle tells us the driver shifted early.*

In ***Figure 3.10***, some overlap is evident in the 2nd to 3rd gear shift. The 3rd to 4th shift overlap is about as small as possible and looks good. The 4th to 5th shift shows minor overlap, but from 5th to 6th there is a lot of overlap caused by shifting early.

There are always exceptions to any rule. Overlap might be acceptable at times for these reasons:

- Driver is purposely shifting early (short shifting) to save fuel.
- Shifting early before entering a high speed corner in order to maintain better vehicle balance and make the throttle less sensitive.
- Shifting into the next higher gear might not be worth the loss in time shifting, if nearing the braking point for the next corner.

Overlaps should be analyzed to determine if valid reasons exist for it. Overlap with partial throttle is acceptable based on the assumption that the driver isn't asking for more power so being in a lower gear won't help.

Unlike gear selection programs, a plot from actual data does not show speed versus RPM in a perfectly thin line. Reasons for variations include:

When using driven wheel speeds:

- Any time the clutch is pressed, the direct connection between engine RPM and speed measurement becomes separated
- Rolling circumference change due to loads on the tire

When using rolling wheel speeds:

- Tire slip during accelerating increases engine RPM and driven wheel speeds but not rolling wheel speed, i.e. ground speed.
- Changes in the tire rolling circumference under braking loads.

In order to minimize the variance, always try to use drive speed. Compare ***Figure 3.9*** created with driven wheel speed to that of ***Figure 3.11*** created with rolling wheel speeds.

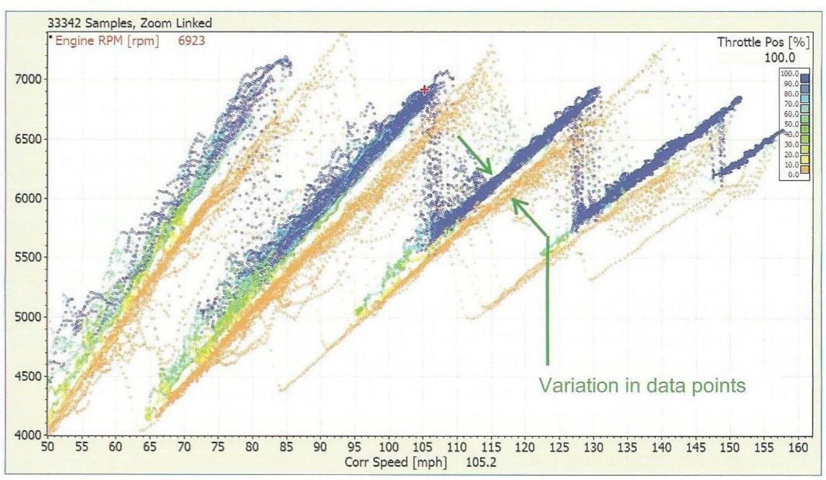


Figure 3.11 *Same data but with rolling wheel speed instead of driven wheel speed. Notice the variance is greater (same number of data points).*

While a X-Y plot provides a good quick visual overview for all the laps in a session, it cannot convey as much information as a squiggly line. It is always important to look at the RPM trace one lap at a time when drawing conclusions about shifting. And don't forget to look at many laps, not merely the fastest.

3.4 Optimizing Shift Points

Many racing series will limit the engine RPM as a way to control power. In these situations maximum horsepower most likely occurs at or near that limit. For all other engines, horsepower will drop off before reaching the RPM limit as determined by the engine builder. If peak horsepower of an engine occurs near the limit, then the best engine RPM to shift at will be that limit. If horsepower peaks too far below the RPM limit, then it might be better to shift at a lower engine RPM. To find the optimum engine RPM to shift at, the gear ratios and a horsepower or torque curve for the engine must be known.

△ Warning: The goal is not to shift at maximum horsepower, maximum torque or the RPM limit. Rather it is to shift in a way that maximizes the engine's running time at its highest possible horsepower.

Engine horsepower climbs up slowly, and falls off more quickly after the maximum. Peak torque occurs at a lower engine RPM. Torque and horsepower are mathematically linked together by engine RPM through the following equation:

Power = Torque * RPM / 5252

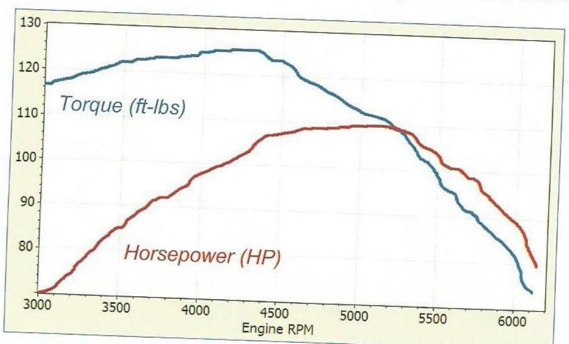


Figure 3.12 *Engine curves for the Spec Racer Ford.*

Optimum shifting is done to maximize the amount of power or tire torque put out by the engine for any given speed. Gear ratios are selected to maximize the area or time spent under the power curve. Since horsepower is calculated from torque and RPM, it doesn't matter which one you use. But finding the optimal shift points via horsepower is much easier because it saves one calculation step. Applied torque through the tires change when going through each gear in the gearbox, but power output doesn't. So when using torque values, the torque curve must be multiplied by the gear ratios to determine the torque out of the transmission and ultimately through the tires at the given speeds.

Picking Shift Points by Horsepower Curve

First create the X-Y plot of speed & RPM, using the gear ratios and tire circumference to calculate speed for each engine RPM. This chart is used to determine the engine RPM drop for each gear shift. Many different software programs for selecting gear ratios are available to create charts like this, or use a spreadsheet program with the following equation:

Speed(mph) = RPM * 60(min/hr) * tire circ.(in) / 63360(in/mile) / Gear Ratio

Starting with the first shift, assume the shift occurred at the RPM limit. Find the RPM drop to the next gear by drawing a vertical line on the X-Y plot of speed & RPM. Then compare the horsepower at both engine RPMs. If the power in the next gear is less, then the shift point should be higher. If the power in the next gear is more, then the shift point should be lower. Continue this cycle until the two RPM points straddle the horsepower curve at the highest section possible for that gear change. This insures maximum time is spent in the largest area of engine power. Do this for each shift through the gears.

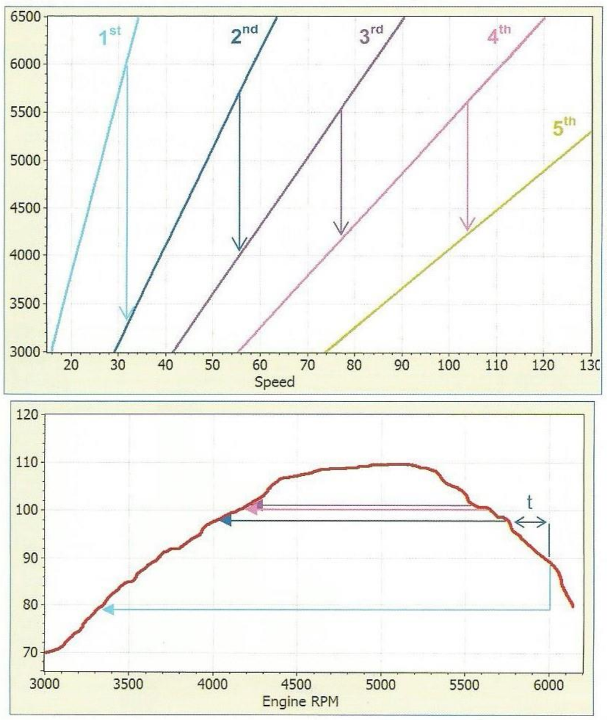


Figure 3.13 *Gear and power curves used to find optimal shift points for the SCCA Spec Racer Ford.*

The following example is from a SCCA Spec Racer Ford (SRF). For this car the gear ratios are fixed and cannot be changed. The ideal shift point from 1st to 2nd would have been 6100, but the engine's RPM limit is only 6000 so that value is chosen. This is the largest RPM drop due to the gear ratios being farther apart, which often means shifting at the limit is best.

Gear ratios for SRF		
Diff	-	3.62
1st	-	3.42
2nd	-	1.84
3rd	-	1.29
4th	-	0.97
5th	-	0.73

For 2nd to 3rd the ideal shift point is 5750 which drops the engine down to 4000 and both engine speeds give 97 HP. If the driver had shifted at 6000, then the amount of time spent accelerating from 5750 to 6000 would have happened with the engine making less than 97 HP (shown in ***Figure 3.13*** as "t"). Shifting at 5750 keeps the engine power always above 97 HP.

Ideal shift points for SRF

	Shift RPM	Drop RPM	Power HP
1st to 2nd	6000	3300	89 to 78
2nd to 3rd	5750	4000	97
3rd to 4th	5600	4200	100
4th to 5th	5700	4150	101

Engine RPM	Percent
0...<500	2.50
500...<1000	0.14
1000...<1500	6.84
1500...<2000	1.40
2000...<2500	2.25
2500...<3000	2.14
3000...<3500	1.40
3500...<4000	1.31
4000...<4500	1.04
4500...<5000	0.78
5000...<5500	4.81
5500...<6000	8.22
6000...<6500	7.81
6500...<7000	13.28
7000...<7500	14.85
7500...<8000	18.09
8000...<8500	12.42
8500...<=9000	0.68
>9000	0.04

Table 3.1 *Text Histogram*

3.5 RPM Histogram

The RPM histogram shows the percentage of time an engine operates in different RPM ranges. Does the engine spend more time in the 6000 range or the 7000 range? While there isn't much a driver can use this data for while on the track, it is important for the engineer and engine builder to know. The engineer might want to make sure the car is geared correctly to keep it in the power band. An engine builder might be able to adjust the tuning of the engine or the design of its components to optimize a certain range of RPM.

When setting up a histogram it is common to ignore any RPM data while the car is idling or not moving. The easy way to accomplish that is to change the range of the x-axis so it only reports on ranges of RPM higher than idle. Each track will generate a slightly different RPM histogram.

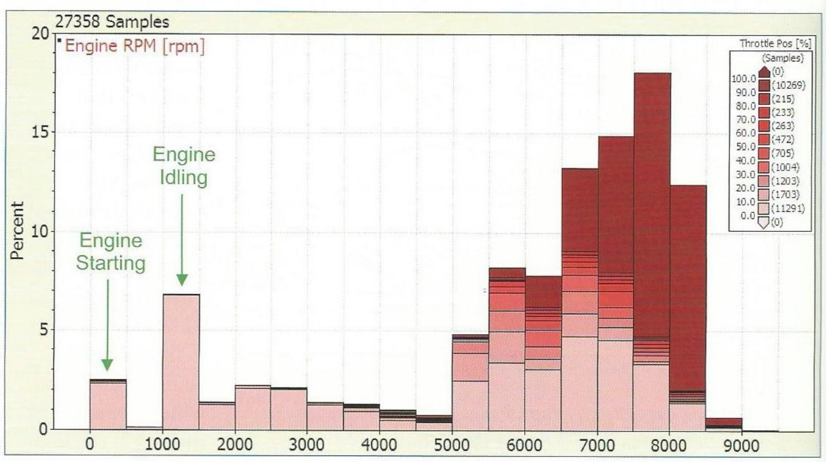


Figure 3.14 *RPM bar histogram shown with a bin width of 500 rpm.*

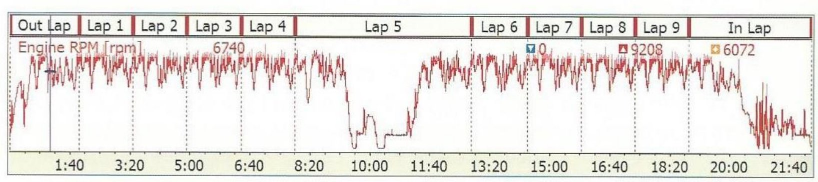


Figure 3.15 *A graph of the data sample used in both histograms on this page.*

Chapter 4 Gear

Gear position sensors are common and easy to mount on sequential gearboxes, but not on gearboxes with a typical H-pattern shifter. In this case the gear position must be calculated by the data system using engine RPM and speed, as long as the gear ratios and tire diameter are known. This calculation does not work if the car is not moving. Nor will it work if the clutch pedal is pressed or the gearbox is in neutral. So as long as the car is in motion and in gear, the calculation works quite well. If you display this calculated gear on the dash, remind the crew members that the car must be moving in order for it to work. Imagine the look on a mechanics face when he or she sees 0 on the display, thinks the car is in neutral and attempts to start the car only to have it lurch forward because it was in fact in gear! I've seen this happen.

To determine which gear the car is in add a gear trace to the graph as shown in ***Figure 4.1*** below.

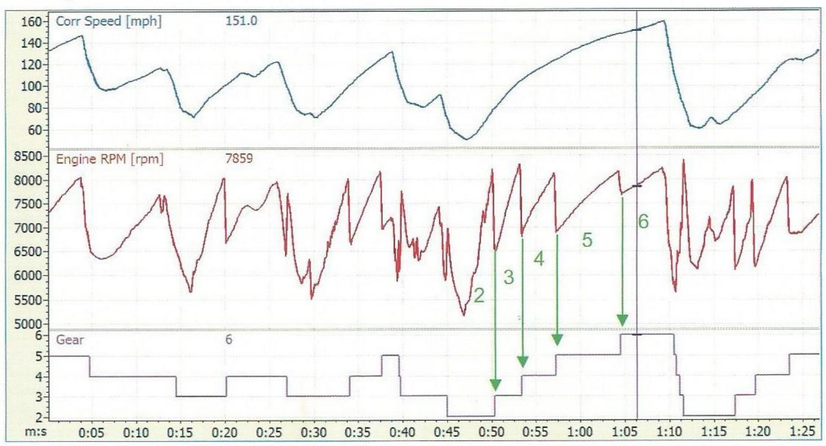


Figure 4.1 *Gear changes are reflected in the engine RPM trace at Road Atlanta.*

When comparing laps, it will be easy to detect from engine RPM alone the locations where each car is in a different gear. In ***Figure 4.2*** the large differences in engine RPM correlate to the areas where different gears are being used. Because a car accelerates faster in lower gears, it is best to keep the car in the lowest possible gear for any given speed. But there are always exceptions to every rule. A short list of reasons to remain in a higher gear are:

- Driver is trying to save fuel by running at a lower engine RPM.
- More gear changes during a lap can increase the chance of a botched shift, losing more time than would otherwise be gained. Having to change gears while in the middle of a corner can be dangerous.

- Certain corners can be driven faster in a higher gear. Such sections are typically fast sweepers or S's where shifting up a gear desensitizes the throttle allowing the driver to be smoother and not upset the balance of the car. Moving the throttle pedal in a higher gear transfers less weight than a lower gear due to lower acceleration and lower torque values on the tires.
- Extra down shifts can disrupt braking, and up shifts delay acceleration. Any gains during acceleration in a lower gear must outweigh time lost during gear changes.

Three locations appear in ***Figure 4.2*** where the laps are in different gears:

1. The driver of the red trace braked later than the black one. Judging from the speed trace, the red trace entered the corner with too much speed and overshot it. The exit speed was so low, that any advantage in acceleration with a lower gear coming out of the corner was nullified. A potential bigger issue is the over rev at the time of down shift!
2. Here the corner entry speed was also higher, but the driver managed to carry that speed through the corner and not hurt the exit speed. Not trying to brake later as the red trace did in the first corner, likely meant the driver this time wasn't in over his head. And even though carrying more mid corner speed was likely more difficult to drive, it was ultimately faster.
3. The driver of the red trace up shifts early to prevent shifting gears in the middle of the corner, and to help desensitize the throttle. This keeps a more balanced car by being smoother for the last turn at Mid-Ohio but the variance channel should be checked to see which is faster.

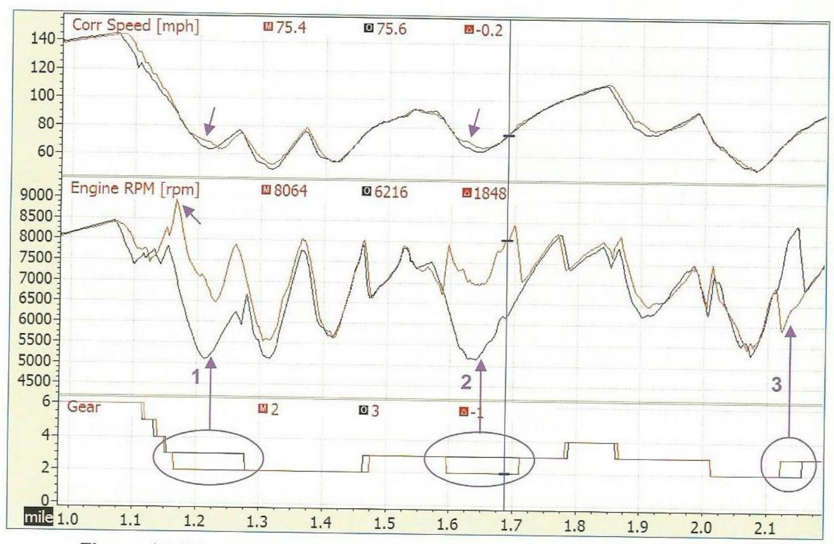


Figure 4.2 *When comparing laps, large differences in RPM correlate to the use of different gears.*

Chapter 5 Throttle

An engine can be thought of as an air pump. To make power, it needs air to burn the fuel. The driver has control over how much air is allowed to enter the engine through the movement of the throttle pedal, which rotates the throttle blade, opening or closing the throttle body. The engine computer controls the mixture ratio of fuel to air and so determines how much fuel the injectors squirt into the engine. In summary, the engine's power is controlled by the driver through the throttle pedal.

Throttle position is a channel that moves between 0 and 100 percent. Some cars have sensors that read throttle angle in degrees or volts or even A-D counts. Converting these into a 0-100 percent scale will make things much easier to understand and compare. This can be done in the logger before recording the channel values or afterwards in the math of the analysis software. Most loggers set this up internally before logging the channel.

Due to the geometry of the throttle system, the percentage values of throttle position do not correspond linearly to the engine's power output. A throttle position of 50% is not 50% power. The geometry of the pedal and throttle blade produce a non-linear relationship between throttle position and engine power. The throttle is very sensitive down low and less sensitive up high.

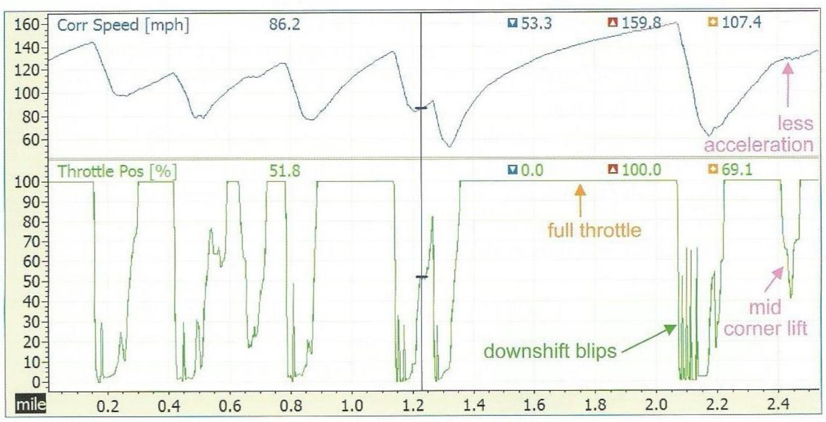


Figure 5.1 *Throttle trace shown in green for a lap around Road Atlanta.*

△ *Warning:* Sometimes the throttle position sensor might only read 99% or 98% instead of 100%. This is most likely a calibration problem rather than a linkage problem. Either way there is little need to fear. The amount of power difference between the throttle being at 98% versus 100% is practically undetectable on any engine dyno, and certainly not on a race track.

5.1 Throttle Blips

Blipping the throttle and down shifting should become second nature to the driver. He or she should never have to think about it. It is a skill the novice driver has to master before going fast.

The goal of throttle blipping is to time them just right when down shifting gears in order to match the engine revs required for the next lower gear. This reduces the impact of letting the clutch out and can make it possible to shift without the clutch.

Down shifting w/o clutch:

1. Take the car out of gear and into neutral
   *on a sequential gearbox, this step is combined with #2
2. Blip throttle the perfect amount till the engine revs match that needed for the next lower gear
3. Push the gear lever into the next lower gear

Down shifting with clutch:

1. Push the clutch in
2. Blip throttle the perfect amount till the engine revs match that needed for the next lower gear
3. Push the gear lever into the next lower gear
4. Let the clutch out

All of this happens very quickly as if it was all done at once. In both cases, the critical timing is #2 and #3. If done correctly the down shift is smooth and has no effect on the balance of the car. If done incorrectly the rear tires lock up and send the car into a flat spin.

If the throttle blip is too little, then the engine braking caused by forcing a down shift will suddenly lock up the rear tires. This upsets the balance of the car when braking. If the throttle blip is too much, the engine accelerates the rear tires which decreases braking and pushes the car forward. To much or too little will both cause confusion when determining the correct brake balance.

Depending on the type of differential, sometimes down shifting helps braking effort by putting a load on the differential. This can prevent a single tire from lockup as the other tire keeps it rolling because the differential acts like its locked together. This results in more total rear braking efficiency as the tire with more grip can produce more braking forces.

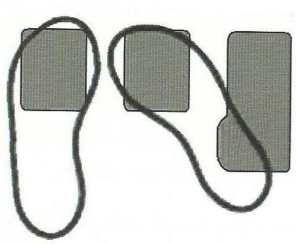


Figure 5.2: Braking with the right foot and blipping the throttle can be tricky.

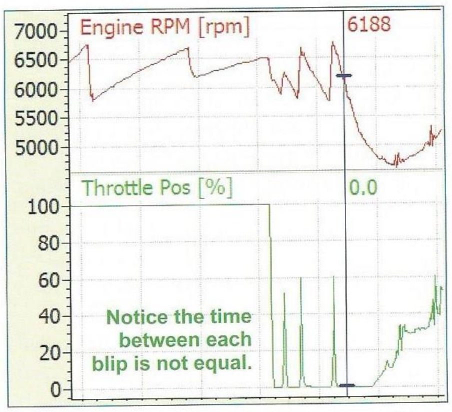


Figure 5.3 *Three throttle blips were made, one for each downshift.*

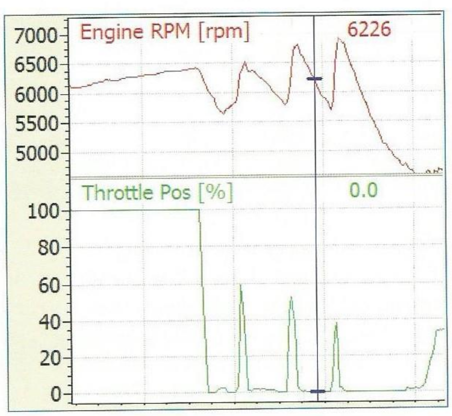


Figure 5.4 *Downshifts are often rushed more and more with each successive one. These are clean but not spaced properly.*

In ***Figure 5.3*** good down shift blips are shown. The RPM rises from the short throttle blips but not over the RPM limit. The blips are all symmetrical and consistent. Also notice more time is needed between shifts with each lower gear. This is necessary as the gearbox makes a larger ratio jump with each shift down.

Also important is the shape of each blip. They should appear clean and crisp. If not, then each down shift could have a negative effect on braking and handling. Down shift blips tell a story of how well a driver handles the pressure of braking and entering a corner at the same time. Most importantly throttle blips show us how consistent a driver is. And inconsistency leads to slow lap times and continual gearbox problems.

This is a very busy time for the driver, so it's easy to make mistakes of rushing the down shift. Accomplishing the down shifts early allows for more time to be spent concentrating on the upcoming corner. But to the mechanic, earlier down shifts require more time spent doing gearbox repairs. The graph in ***Figure 5.4*** shows how the down shift RPM kept increasing with each successive down shift. It is a clear sign the driver needs more patience. Notice the time between each blip is more equal when it should have been longer for each shift down. Notice also the driver blips less for each down shift, when in fact each gear down typically requires more blip because the RPM difference gets larger with a bigger spread in gear ratios. Good down shifting flows naturally, bad down shifting doesn't.

A worse sequence of down shifts would look like ***Figure 5.5***. Here the first and third down shift blips are not enough. The blips are also not timed correctly like in ***Figure 5.3***.

Brakes & Throttle at the same time

In ***Figure 5.5***, notice how the driver never comes completely off the throttle between the 3rd and 4th blips. Being on the throttle and brakes at the same time doesn't help the act of down shifting, nor the goal of slowing down the car. But it will build up extra heat in the brakes. When braking and blipping, make sure to return the throttle back to 0% between each blip. Overheating the brakes can happen accidentally and often unknowingly by the driver. And it can happen when either foot is being used for braking.

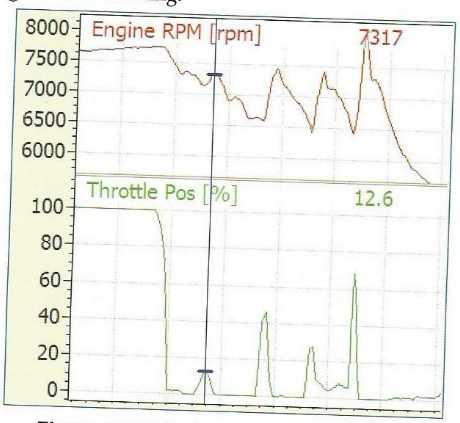


Figure 5.5 *Major inconsistency in blips for both size and timing.*

While common in karting, this type of behavior can be confusing for the ECU or engine control unit. The ECU uses a strategy called *Over Run Fuel Cut* to conserve fuel. It stops all fuel from being injected into the engine when the car's momentum is keeping the engine turning. This increases fuel mileage. Applying throttle over some threshold set in the ECU will turn this fuel conservation off.

Another common problem while down shifting is the release of the brake pedal while trying to blip the throttle. This is best seen with a brake pressure trace, but can also be seen by a keen eye in the G Force Longitudinal trace. As the driver twists their right foot from the brake pedal to the gas pedal for throttle blips, the foot releases pressure off the brake pedal. Without maximum pressure, the braking zone increases and the driver is faced with going into the corner too fast or having to brake too early both resulting in a slower lap time.

While not as common, the reverse can also happen where the driver steps harder on the brake pedal while blipping. If this happens it is clear the driver could have and should have been braking harder to begin with. The solution is to get the driver to brake harder throughout the entire braking zone. Easier said than done. Put on an old set of tires and have the driver purposely lock up the brakes in every braking zone. How else will he or she find the limit?

In conclusion, blipping the throttle for down shifts should have no influence on the brake pedal pressure.

5.2 Average Throttle Position

Most data analysis software programs can calculate the average throttle position for each lap. This number is different from track to track as it depends on the configuration in regards to the number of turns, braking zones and straights. An oval track which is flat out will have an average of 100%, whereas typical road courses vary from 60% - 80%.

Generally speaking there is a correlation between higher throttle averages and lower lap times. Simply put, a driver who is on the throttle more should be going faster. This is not always the case, as a driver who carries more speed through a corner will get on the throttle later and have a lower throttle average.

The throttle average can be used to help compare drivers. Remember to look at all the laps and not simply the fastest. Without analyzing multiple laps for trends, conclusions cannot be fully verified. If the fastest lap had a lower percentage than expected, analyze that lap to find ways for the driver to save fuel.

A typical channel report table is shown in ***Table 5.1*** below. It will be easy to see trends between lap time and percentage of full throttle. For a driver this information might not make him go faster, but for the engineer it will help quantify lap times and estimate how fuel used per lap might change.

		Long Beach, 2008 World Challenge 8:37:12 AM, Practice 2								
		Lap 2 [1:32.188]	Lap 3 [1:31.393]	Lap 4 [1:29.814]	Lap 5 [1:29.321]	Lap 6 [1:28.636]	Lap 7 [1:28.548]	Lap 8 [1:30.215]	Lap 11 [1:27.926]	Lap 12 [1:28.072]
Throttle Pos [%]	Avg	45.8	44.5	49.4	51.2	52.0	52.1	50.6	53.4	54.4
Throttle Pos Full [%]	Avg	28.57	27.96	31.38	35.96	38.61	40.53	36.11	38.85	42.52

Table 5.1 *Average throttle normally follows lap time.*

		Long Beach, 2008 World Challenge 8:37:12 AM, Practice 2								
		Lap 2 [1:32.188]	Lap 3 [1:31.393]	Lap 8 [1:30.215]	Lap 4 [1:29.814]	Lap 5 [1:29.321]	Lap 6 [1:28.636]	Lap 7 [1:28.548]	Lap 12 [1:28.072]	Lap 11 [1:27.926]
Throttle Pos [%]	Avg	45.8	44.5	50.6	49.4	51.2	52.0	52.1	54.4	53.4
Throttle Pos Full [%]	Avg	28.57	27.96	36.11	31.38	35.96	38.61	40.53	42.52	38.85

Table 5.2 *Same data, only reordered based on lap time.*

Note: Notice in the table above, some lap numbers are missing. Those missing laps were either out laps or in laps where the driver travels along the pit lane instead of the race course. Doing so invalidates many things in report tables and therefore should be excluded whenever it makes sense.

Full Throttle Percentage

In addition to the average throttle and for oval tracks that aren't flat out, a full throttle percentage channel makes more sense to use. This number is the percentage of time over one lap that the driver is at full throttle.

△ *Warning:* The throttle channel might not always rest at exactly 100.0% when at its maximum. So anything above 95% should be considered full throttle. When doing any analysis on throttle, use conditions for the cut off value of full throttle to be "greater than 95%" rather than "equal to 100%".

5.3 Throttle Lifts

Fast Corner Throttle Lift

Imagine a fast sweeping corner, one that is grouped into that elite category of corners known to *separate the men from the boys*. Drivers love to make the claim, "I take that corner flat out". Now with data logging the truth can be told. Sometimes a driver doesn't even know they are lifting. Many of these corners can be downright scary in some cars while being completely easy in others due to different aerodynamic downforce levels.

Fast corners are the first place to look for more speed. They account for the largest amount of time loss for novice drivers, and the place where experienced drivers can squeeze out that extra tenth of a second during qualifying. They also have big consequences if a mistake is made.

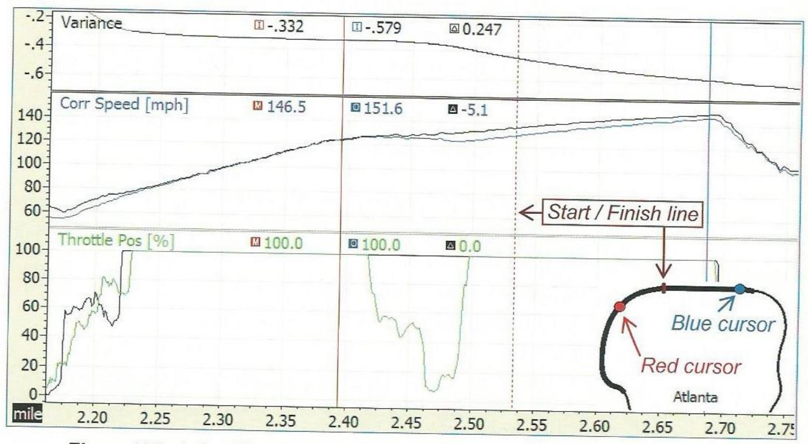


Figure 5.6: *A throttle lift going through Turn 12 at Road Atlanta results in a time loss of 0.247 seconds at the end of the main straight.*

Lets discuss the last turn at the Road Atlanta racing circuit. A LeMans prototype car can easily drive this corner flat out, but in a GT car it's very difficult to do. In ***Figure 5.6*** two laps are shown for a GT class of race car. The red cursor located in the graph corresponds to the red dot on the track. After the cursor, the main lap shown with a green throttle trace and a blue speed trace happens to lift while the overlaid lap in black does not. The throttle trace first drops from 100% down to 50% and continuing down to 10%. This throttle lift decreased the car's speed coming out of the corner and down the front straight. At the exit of the corner, located at the 2.5 mile marker, there is a 7 mph difference. At the end of the front straight the main lap was still down 3 mph. Was this lift caused by handling problems, cold tires, or a lack of driver confidence?

Long Corner Throttle Application

Long corners lead to many different throttle traces, dependant on the driving line and the characteristics of the corner. Some corners have double apexes and others a single apex. Some vehicles won't have enough power so they can run full throttle. Vehicles with more power will require something less than 100% throttle. When this happens two distinct methods arise for throttle application around the corner. One consists of multiple lifts while the second maintains a constant but lower throttle.

If the corner has a constant radius then a more steady throttle might be faster. A steady throttle gives a more stable platform and therefore a more consistent contact patch under the tires. If the corner is long with a changing radius or change in banking, then try the multiple lift method. Also, many race cars have a tendency to push in long corners. So sometimes a little lift near the apex will help rotate the car and change its direction enough to not understeer.

To the right are graphs of Turn 2 at Willow Springs. Notice the slower one on top has larger throttle lifts and spends more time at full throttle. Reaching full throttle is easier when the car is going slower because the tires still have grip available to handle larger accelerations. When the car is cornering near its maximum ability such as in the bottom graph, the tires will be near their peak grip levels where large throttle movements would upset the balance.

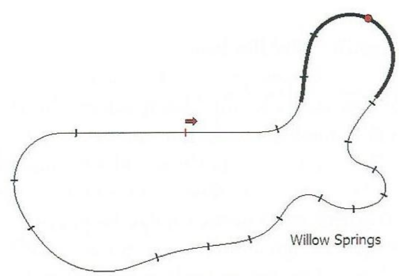


Figure 5.7 The bolded section represents the zoom level for the graphs below.

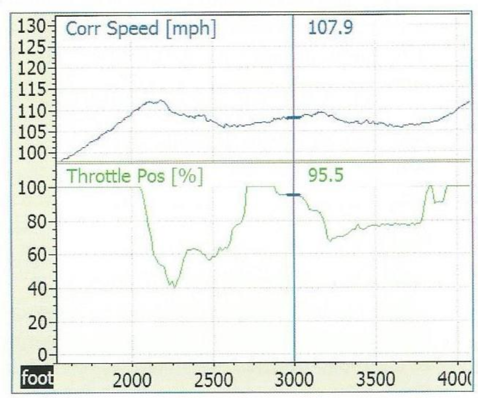


Figure 5.8 Multiple lifts are just one method to get around long corners.

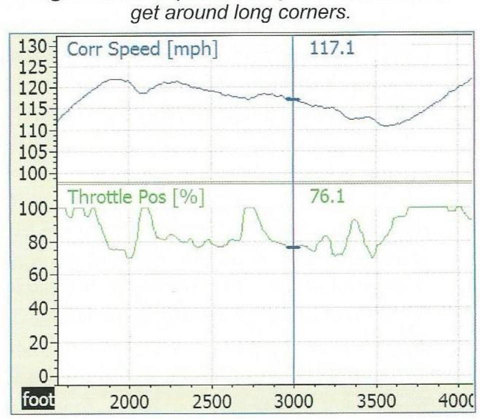


Figure 5.9 Another method would be to use a more consistent throttle amount.

Note: Both examples have the same average throttle!

Corner Throttle Lift

When applying throttle coming out of a corner, the golden rule states there should never be any lifts. If a driver had to lift upon applying throttle, then one of the following conclusions is true:

- The car is pushing and will run out of exit room.
- The car exhibits oversteer and needs less throttle.

While changes to the car can help, drivers can more quickly adapt while on the track through a number of options available to them. Some quick solutions are:

- The driver needs to apex later.
- The driver needs to wait longer before getting on the throttle.
- The driver needs to apply the throttle more slowly.

When tires aren't at their maximum grip level, there will be grip available for the driver to be abrupt with the throttle. Either by squeezing it on early or too hard. Abrupt movements prove the driver can be going faster in the corner.

An early or sudden throttle application can induce understeer. This is caused by weight transfer moving too much away from the front tires and onto the rear. With less weight on the front tires, the tires have less grip to steer the car. Or the driver can create oversteer by applying more power than the rear wheels can handle.

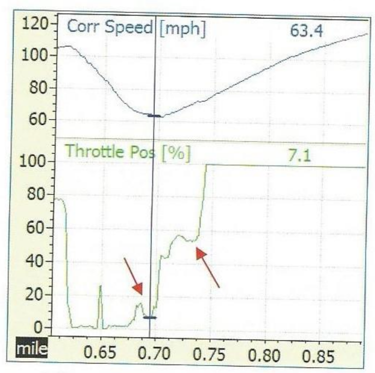


Figure 5.10 *Two lifts on throttle application out of a corner.*

In ***Figure 5.10*** two very small throttle lifts are shown. One right after initial throttle where the driver either lifted to help rotate the car, lifted to reach the apex or realized he or she was too early with the throttle. The data won't tell you everything, so question the driver and on-board video to find out. Then around 50% throttle there is a long pause in application. While a later apex would help, it's more likely a case of getting on the throttle too much too early. The pause helps the driver readjust their line so the car can negotiate the required curvature heading out of the corner. For severe situations, the pause in acceleration can be seen in the speed trace as its acceleration slope decreases during this period of time. The steering trace would also be worth investigating to see if the car was pushing. Looking at the lateral G force might help conclude that the driver was simply going too slow through the corner and that was the reason for such early throttle application. Such analysis is covered later under discussion of the steering angle channel.

For ***Figure 5.11***, throttle lift occurred at the very end of the corner exit, where the driver should have had no problems being at full throttle. This last moment lift happens when a driver realizes they have ran out of exit room! Experienced drivers will make these types of adjustments often on their out lap (the first lap out on track after leaving the pits) because the tires are still cold and generate less grip than when hot.

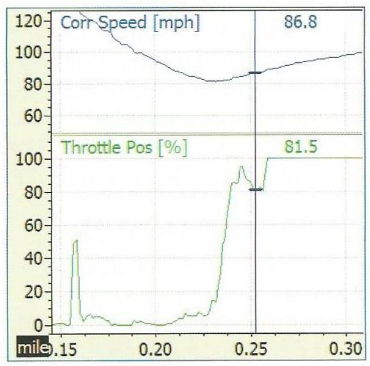


Figure 5.11 Lift right at the exit is typical of a late corner push.

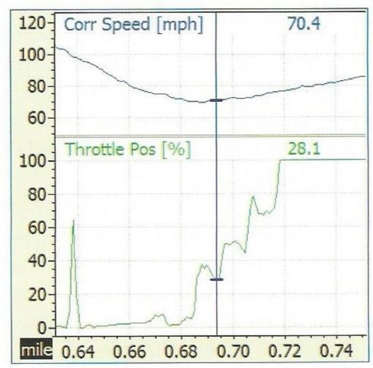


Figure 5.12 Multiple lifts throughout a corner exit signifies a big problem that needs to be addressed with the driver.

When analyzing throttle lifts the steering trace will be very useful. Steering can help in determining if the lifts are from oversteer or understeer. This will be discussed in more detail later. Here the driver feedback is still the most important clue an engineer has. Discuss with the driver what solutions exist for getting rid of these throttle lifts. Adjusting the car might help, or it could be quicker to change the driving line. Experienced drivers will notice for themselves each lift and try adjusting their line during the session. Some drivers aren't aware they are lifting because too many distractions surround them. Changing the car might be easier than changing a driver's habit, but this could ultimately make the car slower. Extreme situations where multiple lifts occur on multiple corners around the track, can be a clear sign of a larger problem that needs dramatic chassis or tire adjustments. Or it could be a track surface that has very little grip!

End of a Straight Throttle Lift

The throttle trace at the end of a straight should normally be a quick drop from full throttle to no throttle, and at the same time the driver steps hard on the brakes. It is one of the few moments that the handling of a race car will not be upset by such abrupt movements. However, many novice drivers get scared at high speeds and that feeling influences their ability to get the most out of the race car. It often leads to early lifting near the end of a straight while they decide when to brake. Keep an eye out for unnecessary lifts at the end of each straight.

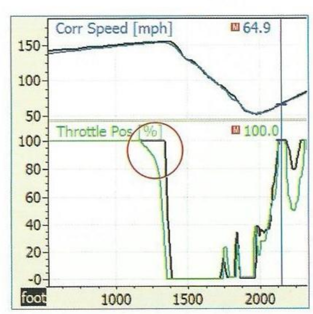


Figure 5.13 Early lifting at the end of a straight.

5.4 Throttle Smoothness

Throttle application cannot be summed up in a channel report table. To analyze, it requires making sense of a squiggly line. Always look for areas that lack in smoothness as these are signs of struggle by the driver. Generally speaking, any significant throttle lift prevents the term *smooth* from being used as a description of the throttle application. Smooth is fast. Its advantage comes from not upsetting the handling or balance of the race car typically caused by weight transfer when making adjustments to the throttle pedal. And that allows the driver to extract the most amount of speed out of a race car.

The transition from decelerating to accelerating shifts weight to the rear. This is called dynamic weight transfer because the weight of the car is moving off the front tires and onto the rear. Similar to stepping down on the gas pedal of a rental car. Eventually the rear will squat and the front will rise. The lower the gear, the greater this effect. While rearward weight transfer is good for rear tire traction, it can be bad for front tires as they still need grip to turn the car through the exit of a corner. Harsh acceleration and quick weight transfer multiplies this effect by the addition of weight transfer momentum. Understeer endures from having less grip on the front tires. This is why it is important for a driver to be smooth with the throttle. If the acceleration out of a corner becomes limited by understeer, it will be the first thing a driver complains about.

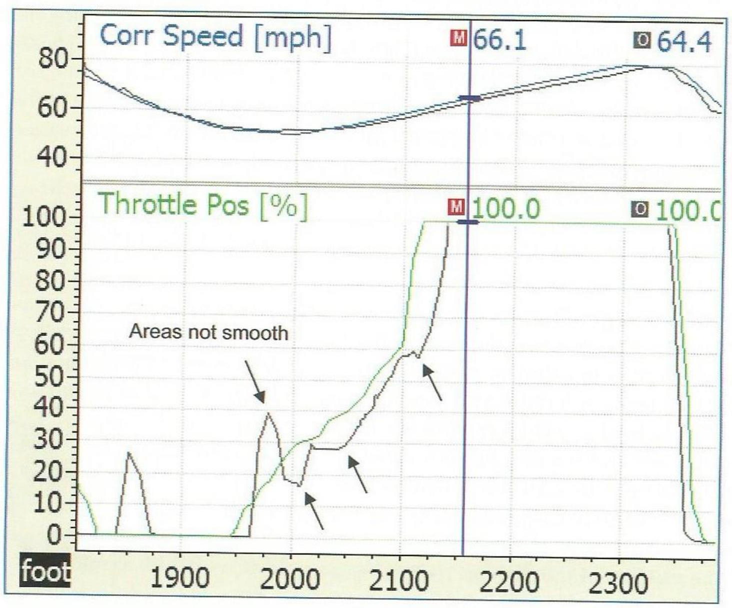


Figure 5.14 *The dark trace is far less smooth compared to the green trace. Notice how the dark trace was slower coming out of the corner, and slower all the way down the short straight.*

5.5 Throttle Application – Ideal Line

The slope or steepness of the throttle trace will convey the speed at which the throttle is opened, known as throttle speed. It can be calculated by taking a math function called derivative of the logged channel throttle. If the corner is driven perfectly, never will there be an exit of a corner where a driver can go from 0% to 100% throttle instantly. There is also no one throttle speed that works for all corners nor all cars. Every corner will be slightly different, but there is an ideal trace of throttle application which can be categorized by a few different stages. An ideal throttle application trace is graphed below.

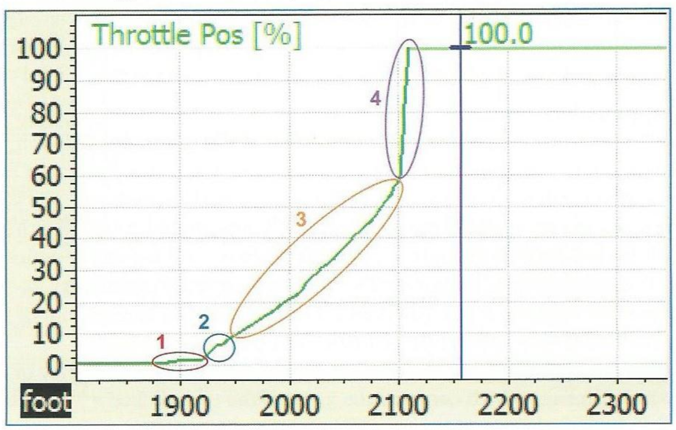


Figure 5.15 *An ideal throttle application trace.*

The four stages of throttle application are:

1. Balanced Throttle
2. Initial Application
3. Middle of Corner Exit
4. End of Corner Exit

Each of these different stages will expand or contract in time based on the corner, driving line, throttle linkage geometry, engine power and handling characteristics of the race car.

Balanced Throttle

Balanced throttle refers to a small amount of throttle which keeps the car at a constant speed, neither accelerating or decelerating. The traction circle, discussed in the next chapter, dictates that maximum cornering forces can only be achieved when the car is at a steady speed. When a driver finishes the braking zone, a small balanced throttle is needed through the center of the turn. The center is not always the geometrical center of the turn, rather it is the section of tightest turning radius and slowest speed where maximum lateral G forces are created. Balanced throttle values will generally never exceed 10% and can be as low as 3% of throttle.

The length of a corner, as well as the type of line driven through the corner all play into effect with how long the balanced throttle time should be. Long constant radius corners will have the longest time period. For an ideal corner the balanced throttle would be the section right at the apex. For a late apex corner it would be the section of tightest turning radii that comes before the apex. The late apex line spends a shorter period of time in the balanced throttle stage.

Balanced throttle is more pronounced with drivers who left foot brake because they use the throttle to effect the balance of their car.

Novice drivers have a habit of coasting. One of the basic rules of racing, a driver should either be on the throttle or on the brakes at all times. Coasting is never allowed. Negative G forces are created from coasting, due to the aerodynamic drag and rolling resistance. The slowing of the car uses up some of the grip that would otherwise be available for cornering when a balanced throttle is used.

Initial Application

The real start to accelerating out of a corner, and the analysis of such, begins with the initial application of throttle. Smoothness is very important here to prevent a driver induced understeer happening early in the corner exit. Those who talk about mid corner understeer might be complaining of understeer in either the balanced throttle stage or the initial application. Verify with the driver which stage the mid corner understeer is noticed. This might not be the stage it starts in. Understeer that happens with a balanced throttle needs to be adjusted out of the chassis differently then understeer that happens on initial application.

The shape of initial application can be dependent on the geometry of the throttle pedal linkage which connects the pedal to the throttle body. This geometry has huge effects on throttle response and drivability. This is discussed in detail during the last stage of corner exiting but applies equally to this stage.

If the initial application is too abrupt, it is possible the driver left out the balanced throttle section. A high throttle speed or quick rise of throttle off 0% can indicate this. Such abrupt driving style can induce a mid corner understeer as the weight is transferred too quickly from the front tires to the rear. And the understeer might not be noticed till later in the corner exit.

Conversely a slow application of throttle might identify a drivers hesitance or lack of confidence. Discuss with the driver why there is hesitation to adding throttle. Throttle equals power which equals speed. If the driver doesn't know why, or can't think of a reason then tell him or her to push harder.

△ *Warning:* In order to find the limit, the car must be driven to its limit. But coaching a driver to drive beyond their talent will result in a crash.

Middle of Corner Exit

Throttle speed in the middle of a corner exit is easily analyzed here but is not as important as the initial application. The middle of the corner exit should have a steady increase of throttle over time.

Note: Fast corners use higher gears than slow corners, so fast corners can handle higher throttle speeds because there is less torque on the tires. But in slow corners the throttle speed should be lower due to the chance of tire spin.

The middle of corner exit stage takes up the longest length of time. As such there is more time available here to influence the driving line. Experienced drivers might use the throttle movement instead of the steering wheel to make last second adjustments before reaching the final stage of corner exit. Once at the exit there is no room to make any more adjustments without driving off track.

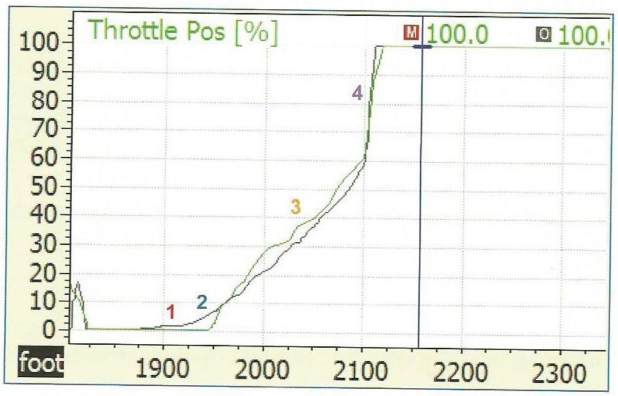


Figure 5.16 *Comparing two different throttle application traces driving out of a corner.*

In ***Figure 5.16*** is a comparison of two throttle application traces. The following conclusions can be made:

1. The black trace is very good with balanced throttle, while the green trace has none. Likely there is some speed left on the table by the green driver in this section.
2. The black trace is very smooth where the slopes blend together between the balanced throttle and initial application stages. The green trace has a relatively good initial application, even if lacking the balanced throttle.
3. The throttle speed in the middle of corner exit is excellent for both, and a little smoother for the black trace.
4. Corner exit throttle is good in both traces.

The amount of engine power which can be utilized when exiting a corner depends on how much traction is available to accelerate forward. A detailed analysis of such will occur in the next chapter on G Forces during the introduction of the G-G diagram and traction circle theory. For now just remember that when in the middle of a corner, all of the tire's grip is used up cornering. When driving down a straight all of the tire's grip is free for acceleration. Between the middle of the corner and the straight, known as the corner exit, there will be an application of throttle equal to the tire grip available as the steering wheel is released.

End of Corner Exit

There are two factors which characterize the shape of the ideal throttle application during its final stage. The first is engine power and torque compared to the available traction exiting a corner. The second effect is based on throttle blade geometry. At some magical point, both of these effects decrease enough to allow a driver the freedom to apply throttle at full speed, instantly.

When exiting a corner a driver releases the steering wheel angle. This frees up some tire grip to be used for forward acceleration rather than cornering. As more grip becomes available there will be a point when the engine power is not strong enough to spin the rear tires. Such point defines the beginning of this stage called the *end of corner exit*. It starts when the throttle can be increased to 100% without fear of exceeding the grip level of the driven wheels.

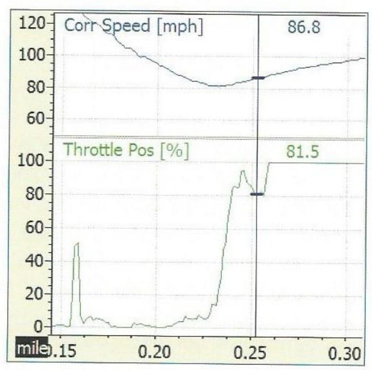


***Figure 5.17** Throttle lift at exit due to understeer or driver mistake.*

Note: Because fast corners use higher gears, the end of corner exit begins sooner than on slower corners.

There is the possibility of driving mistakes that can interrupt high throttle speeds in this stage. If the driver takes the wrong line through a corner, or didn't make the proper adjustments to correct for understeer prior to the end of corner exit, then a driver will abort this stage by lifting off the throttle before their car hits a wall. See ***Figure 5.17***.

The second reason for high throttle speeds during the end of corner exit is due to the throttle geometry at the throttle body. As the throttle blade rotates open, it doesn't form a linear relationship to the opening or cross sectional area of the throttle body. Normalizing these numbers will help in comparing their relationship. In ***Table 5.3***, both the throttle blade angle and cross sectional area are normalized to a range of 0% to 100%. Comparing the rotating angle of the throttle blade to the cross sectional area plots a very non linear relationship as seen in ***Figure 5.18***.

	Minimum	Maximum
Throttle Blade Angle	0 degrees	90 degrees
Normalized to	0 %	100%
Cross Sectional Area	0 mm^2	$(\pi * r^2)$ mm^2
Normalized to	0 %	100%

***Table 5.3** Normalizing values for comparison.*

In this example, 50% of throttle blade rotation creates 70% of the maximum cross sectional area. The cross sectional area relates directly to the amount of air allowed to flow through the engine. That air flow corresponds to engine power. From this XY plot the sensitivity of throttle position can also be examined. At low throttle angles (throttle position < 30%), the cross section changes dramatically. But at high throttle angles (throttle position > 60%) the cross sectional area moves very little. For this reason the throttle pedal which the driver pushes on, is very sensitive down low and not up high.

The initial throttle application when exiting a corner should happen very slowly. Conversely the final part of throttle application will encounter high throttle speeds because engine power doesn't change very much in this region.

Another graph which demonstrates this relationship based on logged data is manifold pressure versus throttle position seen in ***Figure 5.19***. As the throttle blade controls the cross sectional area of the throttle body, it in effect acts like a restrictor to the engine by controlling how much air is allowed to flow through it. This restriction to airflow can be estimated with an air pressure sensor placed downstream of the throttle blade. Notice that only 10% of throttle position equates to about 20% of airflow or engine power. The throttle body might be too large for this engine, hence at 60% opening there is 90% of the possible airflow capable of flowing through the engine. Other factors also influence the amount of power coming out of the engine including back pressure in the exhaust, barometric pressure outside, engine RPM, temperatures and fuel mixture.

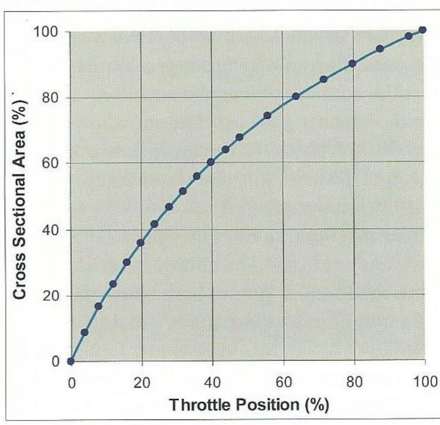


Figure 5.18 *Throttle position versus opened area of throttle body.*

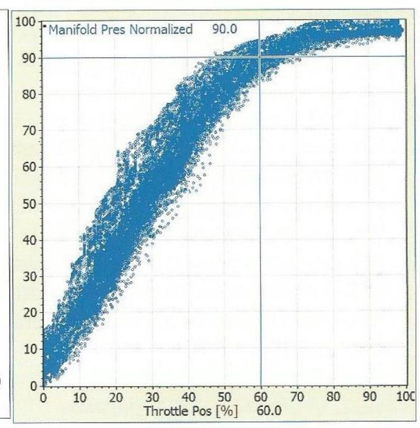


Figure 5.19 *Throttle position versus normalized manifold pressure from actual car data.*

Throttle linkage geometry effects drivability of the engine in dramatic ways. Engine builders are aware of this so many street cars have complex geometric linkages between the driver pedal and the throttle body. Designers attempt to linearize the relationship between throttle position and engine power. With the introduction of Drive By Wire, this welcomed advance allows easy control and the response can be programmed to create an almost perfect linear relationship in the driver pedal.

Chapter 6 G Force

The Earth's gravity which pulls our bodies to the ground is in reality an acceleration applied onto our mass. This acceleration causes the pull or force you feel. When you jump up this gravitational pull accelerates our bodies (mass) back down to earth. Humans don't feel acceleration, only forces. Think about how much effort or force is required to lift a 20 lb dumbbell. Humans relate to forces based on what they know items weigh here on earth and not to acceleration numbers.

The term *force* comes from Newton's Second Law where Force = Mass multiplied by Acceleration or F = M*A. Rearranging that equation also provides A = F / M, or Acceleration equals Force divided by Mass. To make a race car accelerate faster, the force must increase or the mass must decrease. And these equations apply equally when traveling in a straight line or turning a corner.

Newton's equation is the reason why every racing series has a minimum weight rule. Without it, designers would lighten their car to the point where they become too expensive or too dangerous. Once the vehicle can't be lightened any more, the only way to go faster is to find more force. Besides the weight limit many racing series pose limitations to the engine size. This limits horsepower which is the acceleration force in a straight line. A series might also limit the tire sizes. Tire width can place a limit on cornering performance which is acceleration sideways.

To measure these forces we use a sensor called an accelerometer. While it can't measure force, it can measure acceleration. And remember the equation F=M*A? Because the mass of the car is known, measuring the acceleration allows us to calculate force. Traveling down a straight this calculated force equals how much power the engine delivers. When driving around a corner this calculated force equals how much grip the tires have holding onto the pavement.

The forces a driver feels when accelerating, braking or cornering is called G Force. But G Force is a measure of acceleration not force! The G is put in front of Force because the number is normalized to the force of gravity here on earth. Remember though its not truly the force of gravity but acceleration of gravity! Confused yet?

To normalize a number is to convert the number into something more easily understood. One G is equal to the acceleration of gravity or 9.8 m/s^2. Measuring acceleration with a normalized G Force makes the math for comparing forces much easier to understand.

For example, since the driver is fixed into a seat via the seat belt, and the seat is fixed into the car via bolts, the driver also feels the same 2.0 G's when cornering as the car itself. A driver who weighs 100 lb_{mass} will feel 200 lb_{force} pushing against their seat. A driver who weighs 200 lb_{mass} will feel 400 lb_{force} pushing against their seat. The equation F=M*A was used to calculate those force numbers with a normalized G Force:

$$F = M * A = 200\ lb_{mass} * 2.0\ G's = 400\ lb_{force}$$

The units of G's combined with lb_{mass} equate to lb_{force} directly. On Earth, lb_{mass} and lb_{force} are used interchangeably even though they are actually different units. With metric units the same holds true when using kg_{force}:

$$F = M * A = 90\ kg * 2.0\ G's = 180\ kg_{force}$$

But if using Newton for the measurement of force then the normalized G Force would have to be converted back into a direct acceleration number as in the equation here:

$$F = M * A = 90\ kg * (2.0\ G's * 9.81\ m/s^2) = 1766\ N$$

If using direct acceleration numbers with imperial units, the equation would require a conversion for mass to change lb_{mass} into a *slug* (the real imperial unit of mass). A more complicated equation ensues:

$$F = M * A = (200\ lb_{mass} * (1\ lb_{force} /(1\ lb_{mass} * 32.2\ ft/s^2))) * 64.4\ ft/s2 = 400\ lb_{force}$$

Why use G Force instead of actual force numbers?

When comparing different cars with different masses, it is much easier to use our normalized G Force instead of actual force values. For example, you've probably seen performance figures quoted in car magazines as saying "car A can pull 1.02 G's in a corner while car B can only manage 0.93 G's". From that statement the reader would conclude that car A can go faster around a corner than car B. If the magazine were to use actual forces instead of normalized G-Force the same statement would read "car A can pull 2040 lb_{force} in a corner while car B can only manage 2790 lb_{force}". That sentence doesn't make a lot of sense because the reader would have to know car A weighs 2000 pounds and car B weighs 3000 pounds, and then use that to calculate acceleration going around a corner. That's why we use G Force rather than actual force values. It's much easier for comparing and also when writing math equations for analyzing logged data.

Also, when using a normalized G Force number, the quoted performance specifications stay true and equal on all other planets as well!

If you made it through all that, pat yourself on the back. If not, don't worry and simply remember that G Force is how we measure a race car's ability to corner, accelerate and brake. Also remember it's an acceleration not a force.

The Accelerometer

A sensor which measures G-Force is an *accelerometer*. It outputs a voltage to the data logger which is proportional to any accelerations acting on it. The voltage is calibrated into a G Force measurement and recorded inside the logger. They can measure in one direction called a single axis accelerometer, or in all three directions called a 3-axis accelerometer.

Figure 6.1 *A typical 3-axis accelerometer.*

Accelerometer Coordinate System

Many different conventions are in use for defining the directions of positive versus negative. To complicate matters, some accelerometers show these coordinate systems in the opposite direction from the forces acting on a car. Some measure the force an accelerometer exerts back, thanks to Newton's third law of motion; for every force there must be an equal and opposite force. Most, but not all, coordinate systems used in motorsport will follow an orthogonal right hand rule which presents two common possibilities:

Aircraft & Original Automotive Convention:

Axis	Type	Positive	Negative
X-axis	lateral G	right corners	left corners
Y-axis	longitudinal G	acceleration	braking
Z-axis	vertical G	down	up

Newer Automotive Convention:

Axis	Type	Positive	Negative
X-axis	lateral G	left corners	right corners
Y-axis	longitudinal G	acceleration	braking
Z-axis	vertical G	up	down

This book will follow the original automotive convention shown in ***Figure 6.2***. Pay attention to the calibration of your accelerometer in the logger and try to correct any sign conventions to follow one of these right hand conventions. The arrows show direction of positive movement, velocity and acceleration of the car.

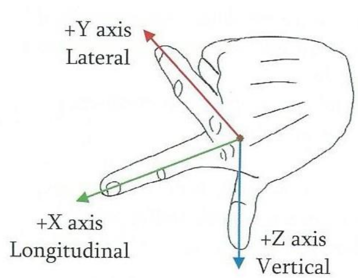


Figure 6.2 *Original automotive convention using the right hand rule.*

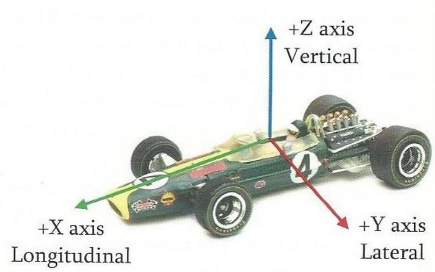


Figure 6.3 *Newer automotive convention using the right hand rule.*

Accelerometer Noise

The accelerometer must be attached to the chassis in order to be subjected to the forces which move the vehicle. Because the sensor measures all accelerations acting on it, the sensor will unfortunately respond to engine vibration through the chassis. Anybody sitting in a race car with the engine running can feel this vibration through the seat. The accelerometer also feels this movement and there isn't much you can do to exclude it. Chassis vibrations are superimposed on top of the normal forces which move a vehicle. The latter is what we want to measure while the engine and chassis vibrations only adds confusion.

The accelerometer should be mounted in an attempt to prevent as much chassis vibration as possible. The normal soft hook & loop tape is almost always the best method for mounting. It absorbs a lot of vibration horizontally and some in the vertical direction. Avoid the harder industrial hook & loop tape. Taking out all of the chassis and engine vibrations is an impossible task, so it is best to minimize the unwanted vibration as much as possible.

In the graph below, chassis vibration is shown by itself in the red trace. The vehicle acceleration which we are interested in logging is shown in the blue trace. The green trace is what an accelerometer actually measures. Both accelerations are added onto one another. A stiffer chassis like those made from carbon fiber will transfer more engine vibration through the chassis and into the accelerometer.

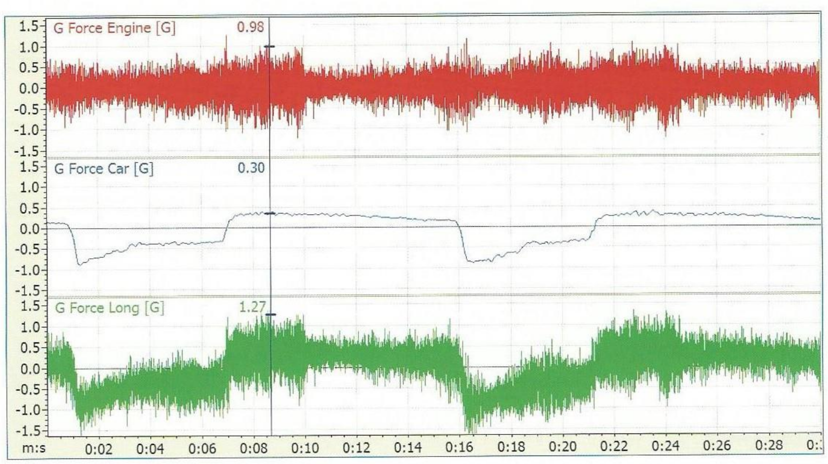


Figure 6.4 *Longitudinal accelerations logged at 500 Hz.*

△ Warning: Many people like to quote G-Force numbers without any filtering applied. The absolute maximum logged value of G-Force, unfiltered, will not be the true G-Force value we are looking for. Unwanted chassis and engine vibration is added to the accelerometer, but has no effect on vehicle motion, thus creating false higher values that should never be used.

Accelerometer Filtering

There are three methods to filtering an accelerometer. Each have their advantages and disadvantages.

1. A low pass filter built into the sensor which filters the channel before it gets into the logger box. It allows the slower vehicle accelerations to pass through but not the higher frequency chassis vibrations. This method increases sensor delay time and might also decrease sensor resolution.
2. An anti-alias filter done by the logging box in real time. It reads the sensor at a very fast rate and applies a center weighted averaging filter to the incoming data before logging the channel at a slower rate. It does require more processing power in the logger box to handle this task and creates a time delay in the signal equal to half the logging rate.
3. Filter applied in the analysis program after logging. This method requires the accelerometer to be logged a very high rates (up to 60,000 Hz) dramatically decreasing the amount of logging time available. Most data systems will have logging rate limits between 100 to 1000 Hz, none of which is fast enough to capture the true vibration necessary before filtering is applied.

Not all of these methods will be available depending on which data system you have. If the data is logged incorrectly, you could end up with bad data as seen in the purple trace shown below. The purple trace reports a maximum of 0.85 G's, yet in reality the gold trace shows less than half that amount. Both were logged at 25 Hz. The gold trace has an anti-alias filter applied to it inside the logger, whereas the purple one does not. If your data system doesn't do any anti-alias filtering, then consider buying an accelerometer with a low pass filter built in.

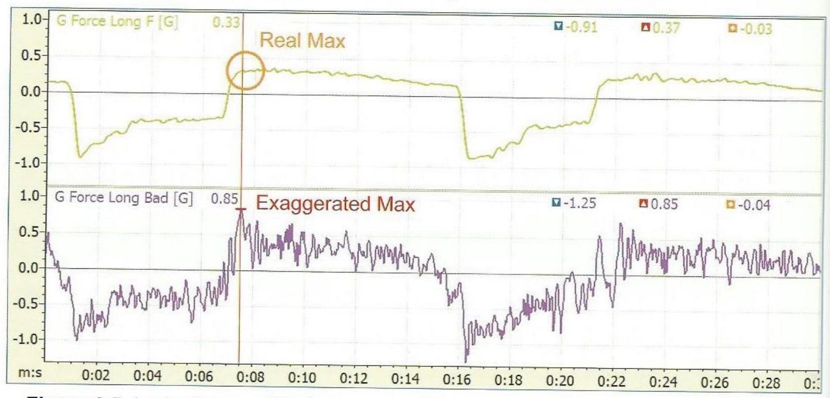


Figure 6.5 *Lack of proper filtering can wreck havoc on accelerometer data. These two traces originated from the same piece of data. Bottom is unfiltered, top is filtered.*

If you must filter the data in the analysis software after logging, then try different amounts of filter and judge the results. The ideal filter will depend on many factors and require some adjusting at first. For time based filters, start with a 0.10 second averaging filter, then try 0.20 seconds and 0.50 seconds. The filter should reduce high frequency bumps but not change the basic shape.

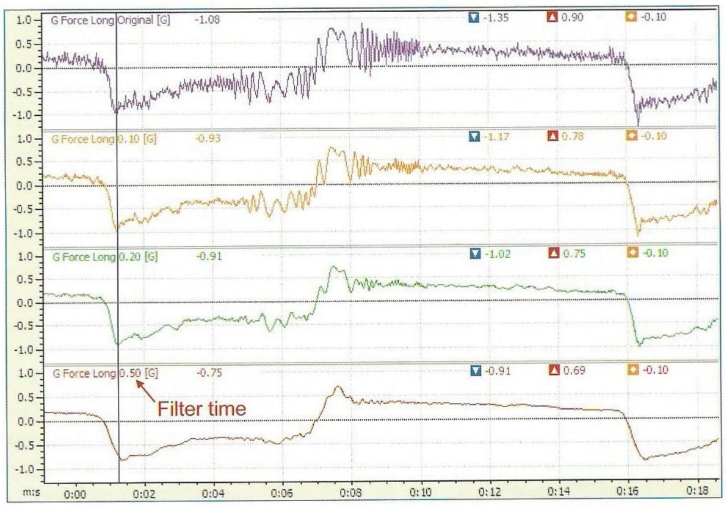


Figure 6.6 *The best filter looks to be the green trace. The larger filter in red smoothes too much as shown in* ***Figure 6.7****.*

△ Warning: Filtering too much diminishes the actual forces of interest.
☑ Check: Always know which channels have filters.

When comparing multiple laps or even quoting G-Force statistics for a vehicle, always add extra filters. The filter should be temporary and removed when the comparison is done. A filter time of 0.30 seconds is a good place to start.

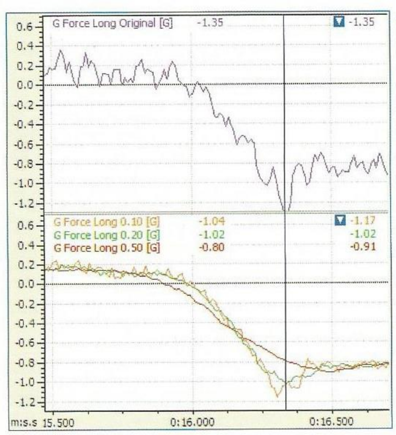


Figure 6.7 *The red trace shown above flattens out the slope during braking, decreases the minimum and shifts the braking point way too much.*

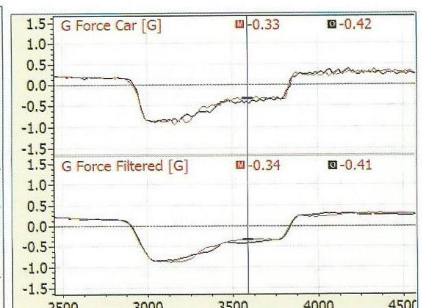


Figure 6.8 *Some over filtering can speed up the comparisons between two laps by making the differences easier to find.*

6.1 G Force Longitudinal - Acceleration

The gold trace shown in the ***Figure 6.9*** is the channel G Force Long. It forms an exponential shaped curve being almost a perfect mirror of the speed channel. This similarity is expected because G Force Long is a derivative of speed. So if you don't have an accelerometer in your race car, the math function derivative can calculated G Force Long from speed. The reason for an exponential shape is due to the governing equation of aerodynamic drag where the speed channel is squared: $drag_{aero} = C * (speed)^2$ When the car reaches terminal velocity, it will no longer be accelerating and G Force Long will measure 0 G's.

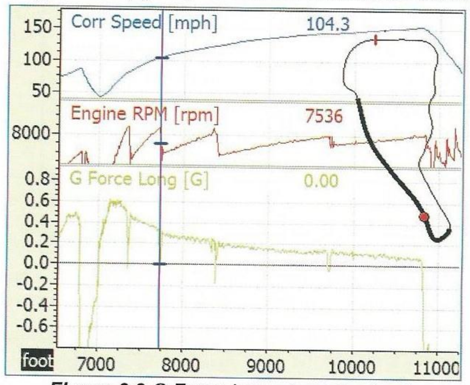


Figure 6.9 *G Force Long down the back straight at Road Atlanta.*

If logged fast enough, short downward spikes will appear at each gear change. These can be easily verified with the RPM trace. The cursor in ***Figure 6.9*** sits directly on a gear change where the acceleration becomes 0 for a split second. The driver makes a total of 4 gear changes during this acceleration run down the straight. Looking at another example, lets analyze ***Figure 6.10***:

1. G Force is greatest in the lowest gear, decreasing with each higher gear.
2. Each gear shift appears as little blips downward where the acceleration momentary pauses.
3. A section that reports artificially lower values, due in fact to driving downhill off the high banking of Daytona International Raceway. Gravity is decreasing the actual measured value for this section.

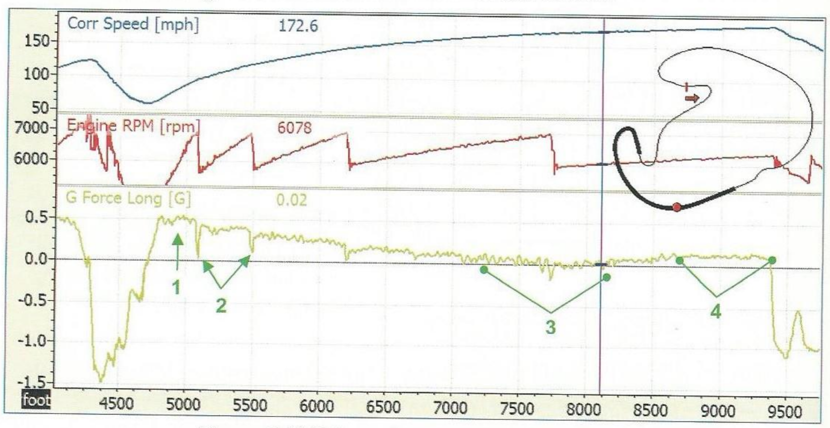


Figure 6.10 *G Force Long graph from Daytona.*

4. Once level again, the G Force value rises, and stays up thanks in part to drafting another car. This drops the aerodynamic drag acting on the car, allowing the engine to accelerate even further.

Four major factors influence a car's longitudinal G Force (ignoring the obvious impact of vehicle weight). Any one of these will change the amount of G Force Long measured during acceleration:

- Different gear ratios
- Aerodynamic drag
- Engine power curve
- Earth's gravity

In 1st gear a car can accelerate much quicker but is limited in top speed. Its high gear reduction allows the engine to generate more torque on the driven tires, resulting in higher G Force Long values. When the car shifts into 2nd gear, the ratio is less and acceleration is lower. This continues for each subsequent higher gear. There is also a difference if the gear ratio is changed for a given gear. So running a 1.666 ratio in 3rd gear will produce higher G Force Long values than running a 1.500 ratio in 3rd gear. Always remember that the limiting factor to G Force Long will be either tire grip or engine power depending on the gear ratio.

In higher gears (a lower gear ratio) the limitation becomes engine power only, based mainly on the aerodynamic drag of the vehicle. This aerodynamic drag causes G Force Long to decrease with increasing speed. Eventually this drag becomes equal to the engine's maximum power, and the vehicle has reached maximum speed. Don't forget about the effects of drafting another car. Drafting either in front of or behind another car will lower the aerodynamic drag on both cars.

Because the engine produces different power at different RPMs, the measured values of G Force Long won't be constant within a given gear. The power curve will in essence appear in the G Force Long trace. This influence is relatively small and not easily detected given the small RPM operating ranges typically used in racing engines.

The fourth and most deceiving factor is gravity. If the car is heading up a 30 degree incline at a constant speed, the accelerometer will measure +0.5 G's even though the car isn't accelerating. Thanks to the effect of gravity. Its effect is added going up a hill and subtracted going down a hill. The pitch angle of the race car will also cause small gravity effects on the accelerometer. As the rear squats down during acceleration, the accelerometer is being subjected to a few degrees of squat or gravity. For basic analysis these pitch angles are small enough to ignore, but the influence from hills cannot be!

△ *Warning:* One of the many pitfalls in data acquisition comes from ignoring any of these factors when analyzing G Force Long. Such mistakes will lead to wrong conclusions. All four factors are superimposed on top of one another, sometimes making it difficult to distinguish what the real value is.

6.2 G Force Longitudinal - Braking

When a driver is braking G Force Long goes negative. The quicker the vehicle is slowing down, the more negative G Force Long becomes. Therefore G Force Long is great at determining the effectiveness of braking. While brake pressure traces are even more useful for driver analysis, the G Force Long channel can still provide lots of information about the car's ability and the driver's ability to brake. Note there is a direct relationship between speed and G Force Long. Either of these channels can be used to verify the other's validity. Therefore it helps to display both on the same graph.

Low Downforce Braking

Once weight transfer has occurred in the transition to braking, a relatively flat plateau of G Force Long should appear. Hopefully reaching the vehicle's maximum rather than being limited by driver talent! Then at the turn in point, steering angle is added as the driver starts to trail brake. Because the front tires will be forced to give up some braking force or grip to steer the car, the negative value of G Force Long should rise back up.

△ Warning: The maximum amount of G Force from one corner to another will not always be the same due to many factors similar to those when accelerating.

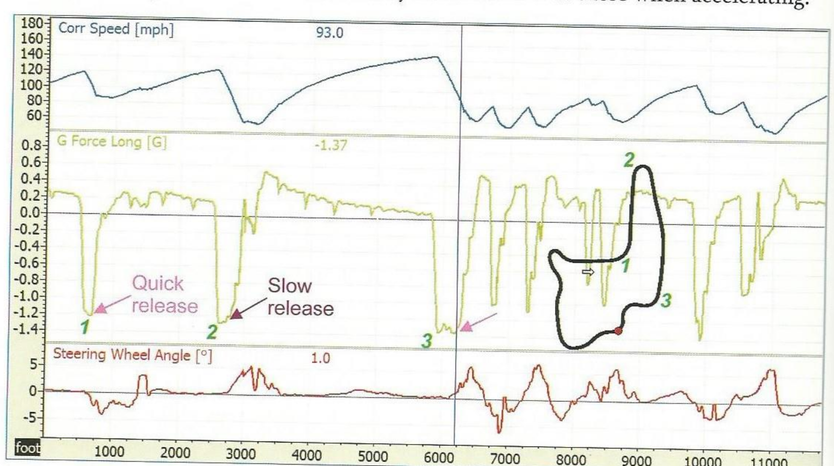


Figure 6.11 *Graph for a low downforce GT race car at Mid-Ohio showing the braking forces from the G Force Long channel.*

A summary of the graph above in ***Figure 6.11***:

- This vehicle can brake around a maximum of -1.3 G's.
- Typical for low downforce cars, G Force Long in Turns 2 and 3 are similar even though the entry speed into braking for Turn 3 is higher than Turn 2.
- The cursor sits at the point where turn in begins. Turns 1 and 3 have very little trail braking as the trace goes up sharply. Turn 2 has more trail braking as the trace curves from the slow release of the brake pedal.

High Downforce Braking

Race cars with high amounts of downforce won't have a flat plateau of G Force Long when braking. Aerodynamic downforce increases with vehicle speed. The faster a car travels the more downforce it creates. Because downforce increases the grip level of tires, higher speeds will allow drivers to brake harder. Then as the speed decreases while braking, so does downforce and the braking ability of the race car. Hence a rise in G Force Long. And finally, at the start of trail braking the trace will rise up even more sharply. Analyzing ***Figure 6.12***, notice the following:

- The cursor location sitting in Turn 1 points to the moment in the braking zone where straight line braking ends and trail braking begins. Notice how the slope of the trace directly after the cursor rises more quickly than before the cursor. This knee in the slope can be used to identify the start of trail braking and should correspond to when the steering wheel starts to move. The steering wheel angle trace is on the bottom for reference. This location is also easily noticed in Turn 5.
- The maximum G's in each braking zone change based on the speed attained just before braking. The first and last braking zones which are Turns 1 and 5 have the greatest negative G forces. Those corners in the middle have less. Notice the maximums are proportional to the speed before braking.
- The speed before Turns 3 and 4 are similar as pointed out by the green arrows, but the maximum G was slightly less in Turn 4. One reason for this difference is the shorter braking zone. It will have a less optimal bias because there is not enough time nor forces to achieve complete weight transfer. But the main contributing factor here in Turn 4 is the trail braking. Less tire grip is available for braking due to the added steering input because the braking zone is curved.

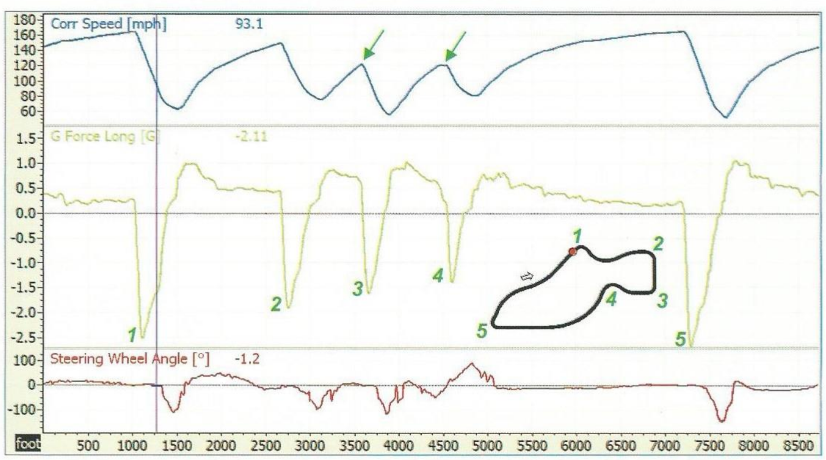


Figure 6.12 *Maximum braking forces achieved before each corner varies with speed on this high downforce formula car on the short Sebring course.*

Braking Point

The trace of G Force Long is great for comparing and measuring the braking points between laps. Remember to verify the graph is in distance mode first. Then use the cursor to measure differences in the lap distance where the G Force Long trace first takes a sudden drop. The distance in ***Figure 6.13*** is found to be 64 feet or about three car lengths. This might seem like a large difference, but to the driver in the car it's not. Remember that when traveling at 140 mph, braking 64 feet later corresponds to only 0.3 seconds. Hardly more than a blink of an eye!

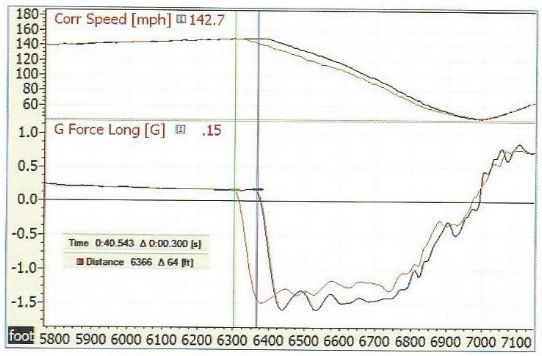


Figure 6.13 *Braking points are easy to see with G Force Long. Distance can be measured where the traces drop to find the difference in braking points.*

More importantly the variance channel can be used to find how much time is gained from this later braking. The graph below of ***Figure 6.14*** is an expanded view of the lap in ***Figure 6.13***. The two cursors which surround the first braking zone, show a net time gain of 0.371 seconds from the mere 64 feet of braking later. While the act of braking later is known to produce faster lap times, it's actually the increase in speed throughout the entire braking zone which lowers the lap time. Notice the variance channel moves down throughout the entire braking zone, not during the actual 64 feet of braking later.

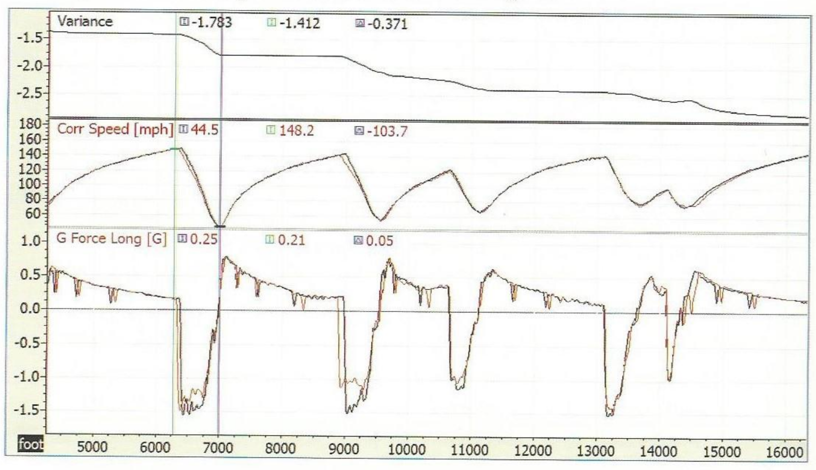


Figure 6.14 *The Variance channel allows for time gained or lost in the braking zones to be accurately measured.*

During a qualifying session, the majority of lowered lap times come from later braking points. A lighter car with less fuel and fresh tires are the perfect conditions for a fast lap. The two laps shown in ***Figure 6.14*** are what you might see as the differences between a race lap and a qualifying lap.

△ Warning: Trying to brake later can cause driver error. The driver can be overwhelmed by the increase in speed while braking. Because it feels too fast some drivers will mistakenly over slow for the corner. Often the driver will over shoot the corner, removing any advantage gained from later braking. Over shoots can lead to data shift from a longer lap distance, resulting in the rest of the lap not aligning correctly.

In ***Figure 6.15***, there are two different driving lines through Turn 1, both equally fast. The red trace brakes 70 feet deeper, but over slows the car by 8.4 mph. This results in a slower exit and all of the time gained from braking later was lost. During analysis, use the variance channel to compare how all of the following sections relate to each other; braking zone, corner and the following straight. Braking later can cause changes to the driving line through a corner, for better or worse. Work with video and GPS whenever possible to be sure of the fastest line.

Looking at Turns 2 & 3, there are again two different driving lines. The red trace does exactly the opposite from Turn 1 and brakes early, yet carries more speed through and after the corner. This time there is a clear advantage to the red trace due to its exit speed out of Turn 3. Obvious from the G Force Long trace, the added speed through Turn 2 required a throttle lift. Could it be caused from the driver feeling unstable? Maybe the driver didn't know where their braking point was for Turn 3 and had to get back on the throttle to reach it? Was another car in their way forcing a throttle lift? Or was the driver just trying a different line through Turn 2? Verify with the driver and check the video and GPS.

Turn 5 looks similar between both laps and shows good consistency.

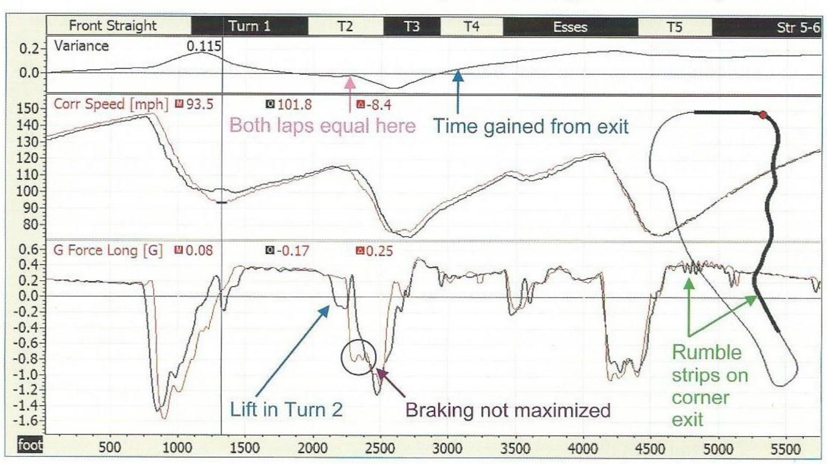


Figure 6.15 *Three corners where the first two have different braking points between the laps while the last braking point is the same.*

Application of Brakes

Race cars with stiff suspension can transfer weight more quickly. Ideal for quick and hard application of brakes. And race cars with a lot of aerodynamic downforce can handle even quicker and harder applications of brakes.

Race cars with soft suspension require patience and sensible applications of the brake pedal. Stepping too hard too quickly can lock up the front tires before weight has transferred to the front which helps keep the tires rolling.

△ Warning: Inexperienced drivers might try to move the bias knob more rearward to prevent front lockups when applying the brakes too quickly. This will decrease overall braking ability. Brakes should be balanced and optimized during the period after weight transfer. This is the longest portion of braking, and should be in steady state which means no movement in weight balance. During braking there could be as much as 75% of the vehicle's weight on the front and only 25% on the rear. That is why the front brakes are larger than the rear, they do more!

As weight is transferring or moving forward, it has momentum. This momentum increases the weight transfer before leveling back off. On loose gravel and dirt, rally drivers perfect their skill of braking and un-braking at the natural frequency of the car, using this momentum to transfer more and more weight onto the front with each press and release cycle of the brake pedal. This helps the tires dig into the loose ground and results in quicker stops.

Note: With the exception of rally driving, braking should always be done with one consistent application for optimal results.

Braking Effort

Braking effort should only be studied in a straight line which is the only place where maximum negative G Forces are possible. As soon as a driver starts the turn in process, tire grip must be used for cornering so G Force will rise back up. Short braking zones should also be ignored because drivers are being smooth and to minimize weight transfer they don't brake as hard. Therefore these such braking areas don't offer much to analyze.

While the slope of the speed trace can be used to estimate braking effort, with G Force Long an actual number can be logged to measure stopping ability directly. Higher braking forces result in more negative G Forces.

Before making any conclusions from looking at G Force Long, always have a quick look at the individual wheel speed traces for lockup. If they aren't showing any partial lock ups anywhere on any lap, then the driver should be braking harder. Another reason why four wheel speed sensors is highly recommended. If the racing series only allows two wheel speed sensors, its best to put them both on the front.

If the G Force Long moves up and down during straight line braking, then maximum braking ability wasn't reached and needs analysis. Often this could be the result of any one of the following reasons:

- A driver realizes they started braking too early and won't reach their turn in point for the corner. So the driver releases some braking force to drive further into the corner, then presses hard again just before turning.

- A driver notices one or more of the wheels have locked up. The driver attempts to modulate the brake pedal force in hopes of preventing damage done to the tire. A quick check of wheel speed traces will verify this cause.
- Sometimes the trace will move up and down each time the driver blips the throttle on down shifts. Sometimes it is the release of pressure on the brake pedal when reaching for the throttle. But don't rule out an increase in pressure when blipping the throttle if the driver wasn't braking hard enough to begin with. The blip can cause an increase in brake pressure.

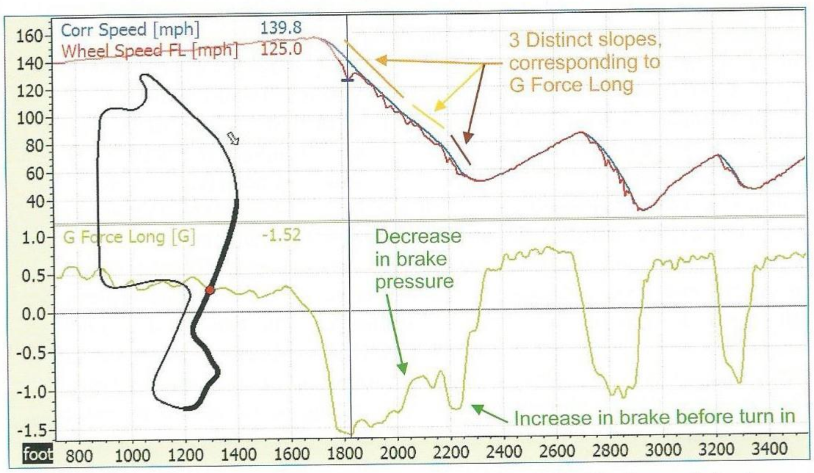


Figure 6.16 *Here heading into Turn 1 at Long Beach, braking too early leads the driver into adjusting the brake pedal pressure. The hard braking early on has a little tire lockup, which is good to see the driver finding the tire's limit.*

One of the biggest improvements to lap time is often helping a driver to brake at the maximum ability of the race car. This cannot be over emphasized. Drivers often brake at what they feel is the maximum, but until a tire gets locked up no one will ever know. Traction sampling (testing the limits) and partial lock ups are the only way to find that limit. Newer cars with ABS are a great training aid for drivers to keep braking harder until ABS activates.

Braking Release

The release of the brakes should not be as abrupt as the application of brakes. This can be a sensitive area for the race car as it transitions from braking to cornering. Weight is transferred off the front tires and onto the rear, while at the same time the addition of steering transfers weight from the inside to the outside. Abrupt movements can upset the car and cause handling issues induced by the driver.

While the release of the brake pedal can effect handling, its speed of release is often governed by trail braking. The technique called *trail braking* requires a slow release of the brake pedal, timed correctly with feeding in steering angle. As more and more braking power is released, more and more steering can be added.

Comparing G Force Long

As a general rule of thumb, if the maximum braking force is -1.5 G's, then a car should be able to brake at that amount in every braking zone. Therefore some people compare each braking zone to see if that maximum or potential is reached in every corner of a single lap.

△ Warning: This is rarely true because each braking zone has a number of variances which can effect the maximum braking G's measured by the accelerometer. Many of these factors are similar to those under acceleration, but braking forces are typically twice that of acceleration so the factors have a larger impact. Those factors are:

- Earth's gravity from hills
- Earth's gravity from pitch angle
- Aerodynamic downforce
- Local track grip levels
- Trail braking
- Tire performance & vehicle weight

The first and biggest concern are hills. The angle of the accelerometer with respect to gravity results in a portion of the gravity affecting the sensor. If a car is traveling uphill, the accelerometer will measure more G's in the longitudinal direction than the actual value accelerating the mass of the car. So not only does gravity effect the reading of the accelerometer, it does so in the wrong direction from its effect on the car. Now if the car was traveling downhill, the accelerometer would measure less G's than the true amount accelerating the mass of the car.
To summarize:

- Accelerating uphill → sensor reads more positive
- Accelerating downhill → sensor reads less positive
- Braking uphill → sensor reads less negative
- Braking downhill → sensor reads more negative

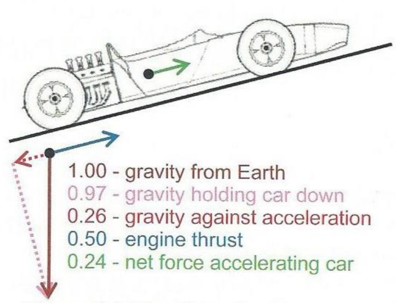


Figure 6.17 *Gravity's effect on hills.*

In ***Figure 6.17***, the accelerometer would actually be measuring 0.5 G's which is equal to the engine power trying to accelerate the car while working against gravity. If G Force Long was calculated via the speed channel or from GPS, it would measure 0.24 G's. This is the right number if you were trying to calculate speed of the car, but the wrong number if you were trying to calculate horsepower of the engine.

The pitch angle of the vehicle creates a similar effect from gravity. As everyone has experienced when pressing hard on the brakes of a rental car, the front dips down while the rear rises. This angle causes the accelerometer to read more negative than what is truly slowing the car down. Its effect is much smaller than most hills but nevertheless should be considered. If the pitch angle is known from suspension sensors, advanced users will subtract out the pitch angle effect on the measured G Force Long. To summarize pitch angle:

- Pitch during accelerating - sensor reads more positive
- Pitch during braking - sensor reads more negative

While adding aerodynamic downforce hurts acceleration and top speed, it does the opposite for braking. Braking forces can easily double or triple in high downforce racing cars. Even sedans with little downforce can generate more braking forces when at higher speeds. When comparing braking G Forces between different corners, the speed attained just before braking has the largest effect on what the maximum negative G Force can reach.

Don't forget about local track grip levels which can change from one braking zone to another. It cannot be ignored and is impossible to measure, but affects the maximum braking G's which are possible in each corner.

Because trail braking requires a release of the brake pedal, its effect is dramatic on the trace of G Force Long. Where the pedal starts to get released is the start of trail braking, and the end of straight line braking. This is easily seen where steering or G Force Lat begins to deviate from zero. The G Force Long trace will also move up and be less negative than the maximum G's reached during straight line braking. It will be a more prominent change than the loss of aerodynamic downforce while braking. Refer back to ***Figure 6.12***.

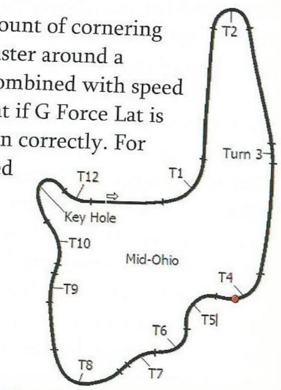
Note: Remember, when comparing the effectiveness of braking always do so when the car is in a straight line before any steering input. Once the steering angle has started to move, the next section of the trace is no longer straight line braking and becomes an analysis of trail braking instead.

The G forces possible during braking are around twice that of accelerating. Therefore tire grip and vehicle weight play a bigger role. As the grip level of tires wear down so does braking performance. This could be noticeable during a long session depending on the tire's characteristics. Alternately the weight from fuel burns off throughout a session, therefore lightening the car and allowing it to stop quicker. The two counteract each other, but likely won't equate to a zero effect. It depends on how much grip is lost in tire wear, versus performance gain from less fuel weight.

On a perfectly level racing circuit with no downforce and consistent grip everywhere, a vehicle should be able to reach the same amount of braking G's in each braking zone. But that rarely happens. Because of those varying factors discussed above, each braking zone is different and must be compared solely between different laps in order for those factors to equal out. So while it can be difficult to compare maximum braking G's between different braking zones of a single lap, comparing the same braking zones on different laps yields valid comparisons (fuel weight and tire wear variation still applies).

6.3 G Force Lateral

The channel of G Force Lat measures the amount of cornering force. A higher number means the vehicle is going faster around a corner. When there is no GPS data, this channel is combined with speed to draw the track map. Therefore you can assume that if G Force Lat is calibrated incorrectly the track map will not be drawn correctly. For more information about how track maps are generated and what can go wrong, refer to Chapter 9.



For basic analysis, there is not a whole lot that can be learned from looking at G Force Lat in raw form. It must be combined with steering and speed for analysis of oversteer and understeer. These will be discussed in the next Chapter.

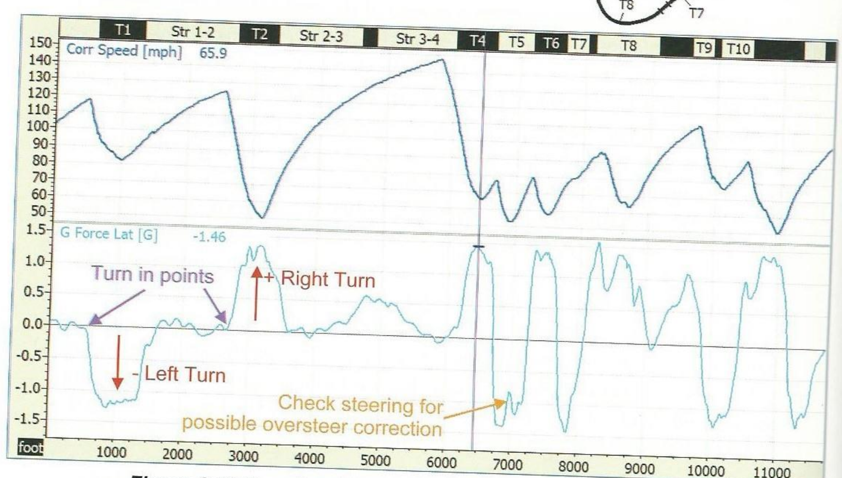
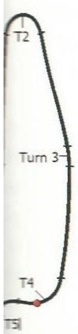
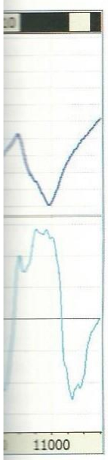


Figure 6.18 *Speed and G Force Lat channels around Mid-Ohio.*

For cars without a steering sensor, the G Force Lat channel can substitute for general analysis. The problem is that you won't know if a drop in G Force Lat is caused by a reduction in steering angle or a loss of grip.

It can be generalized that a car should be able to pull the same amount of G Force Lat in every corner. However, as with G Force Long, local corner deviations can become misleading. The largest influence in incorrect readings are due to banking effects, either positive or negative banking. The more positive banking that exists in a corner, the faster a car can go around the corner. Hence many oval tracks are banked. While driving on a banked corner, the accelerometer will measure less G Force due to Earth's gravity. For long banked corners like those at Daytona International Raceway, it is possible to filter the G Force Vertical channel, and then use that measurement to calculate the actual banking angle.





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The maximum G-Force that can be generated depends on many things, but most importantly the mass of the car and tire grip. Because the minimum weight is often fixed for most racing series, getting the most out of the tires is the only thing that can improve cornering performance. This requires finding the optimum settings for tire pressure, camber, suspension geometry, dampers, etc.

Changes to Car

Comparing G Force Lat can provide insight into which tire pressures or suspension settings will make the car go faster. The best method to accomplish this is to visit the skid pad for some testing. A skid pad is a large paved area where the car drives around in a circle with a fixed radius. By making changes to the car and driving at its limit safely, different setups can be tested in hopes of increasing the maximum cornering G Force. Generally, these changes produce small differences in G Force Lat. Therefore such testing should be done in a very controlled environment with each change repeated more than once. This will help solidify the conclusions.

△ *Warning:* G Force Lat comparisons are difficult every time because any of the following issues will impact the lateral G's recorded:

- Track conditions changing throughout the day. There can be more grip in the morning on a cool track than when the track is hot and greasy.
- Tires start out cold and gain grip when they get hot.
- Tires wear down and the number of thermal cycles decrease tire grip
- Vehicle weight changes with fuel load

Therefore don't get suckered into thinking some change made to the car increased the amount of lateral G forces when the change was due to another factor.

Turn-In Point

The turn in point for a corner can be easily found with G Force Lat. While traveling along a straight, G Force Lat should be near zero. The location where this channel shoots up or down will indicate the turn in point. It will be useful to know when analyzing different driving lines around a corner, and when comparing drivers. A driver that turns in too late or too early, will put their car on a different line through the corner. Steering is a better indicator, but if your data system does not have a steering sensor, then G Force Lat can be used.

6.4 G-G Traction Circle

The G-G Traction Circle is an X-Y scatter plot which has G Force Lat on the horizontal x-axis and G Force Long on the vertical y-axis. This is also called a friction circle. It demonstrates how tire grip can be maximized in only one direction at any time. Yet the biggest use of this plot is to help a driver see their skill in trail braking graphically.

Tire Theory

For a given tire, there will be a maximum amount of grip it can produce through its contact with the surface of the track. The theory states a tire can only drive within the limits of its traction circle. Trying to go beyond this circle is not possible and would result in the car sliding off the race track. A vehicle not moving at all would rest in the center of the circle because it's not generating any G Forces. When a vehicle is not driven at the tire limit, it will be inside the circle. A vehicle driven on its tire limit would be on the edge of the circle.

The length of the arrows in ***Figure 6.19*** represent the grip vector of the tire. Notice this arrow can point in any one direction such as accelerating, braking, or turning. When any of these are combined, the arrow length still cannot extend past the traction circle. Any combination of cornering and braking will result in lower G Forces individually, but combined they could still reach to the edge of the circle. This is the limit of grip available.

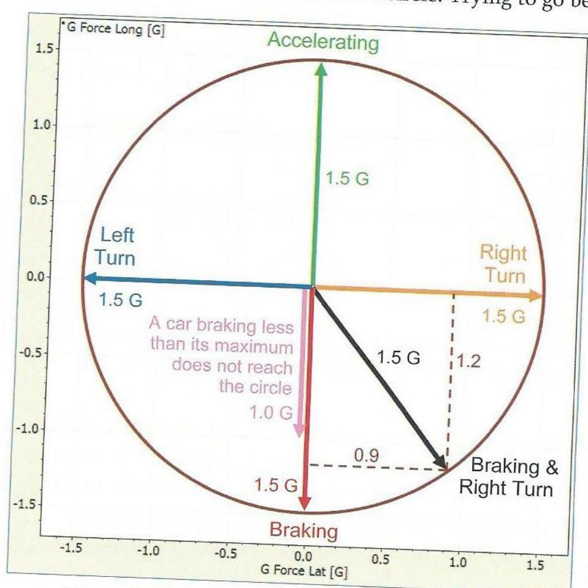

Figure 6.19 *G-G Plot / Traction Circle, max vector length is 1.5 G in any direction.*

In ***Figure 6.19***, the black arrow is a car doing 1.2 G's of braking and 0.9 G's of cornering, creating 1.5 G's of total force. This follows Pythagorean theory of right angle triangles which states $a^2 + b^2 = c^2$. Or for this example; $1.2^2 + 0.9^2 = 1.5^2$.

Note: The radius of the traction circle changes continuously throughout the day as the tires wear, fuel load burns off and the track surface changes. For race cars with high levels of downforce, the radius changes dramatically with speed. Therefore it is helpful to color the dots and lines based off the speed channel.

Real G-G Plot

There exist some noticeable variations from the theorized G-G Plot to a real life example. Remember to make sure the accelerometer channels have enough filtering applied to get rid of chassis and engine vibration. Notice how the top of the circle is chopped off? Most racing cars have only two driven wheels to accelerate. Therefore the car won't be able to generate as much force during acceleration as it can while braking or cornering when all four tires contribute grip. Also, the engine doesn't have enough power to break loose the driven tires while fighting aerodynamic drag. These things combine to flatten the top.

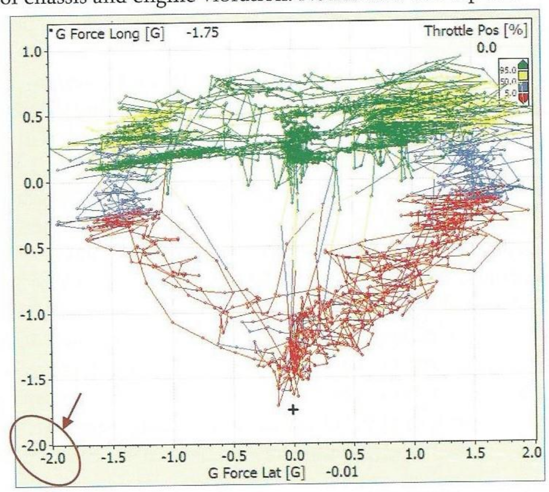

Figure 6.20 *An unfiltered G-G Plot will falsely increase the size of the traction circle, here up to 2 G's.*

The right and left sides might not be symmetrical with respect to lateral G force. For right hand corners this car reaches 1.6, but for left hand corners it only reaches 1.5 G's. This occurs most often due to corner banking and maybe an asymmetric car setup. This particular G-G Plot also has more data points on the right side and therefore must be a clockwise racing circuit. In braking the car reaches -1.6 G's with the help of all four tires, but only manages 0.7 G's in acceleration from the two driven tires. Also note the G-G Plot above has unfiltered data points that reach 2.0 G's, while the filtered one on the left is scaled to 1.7 G's.

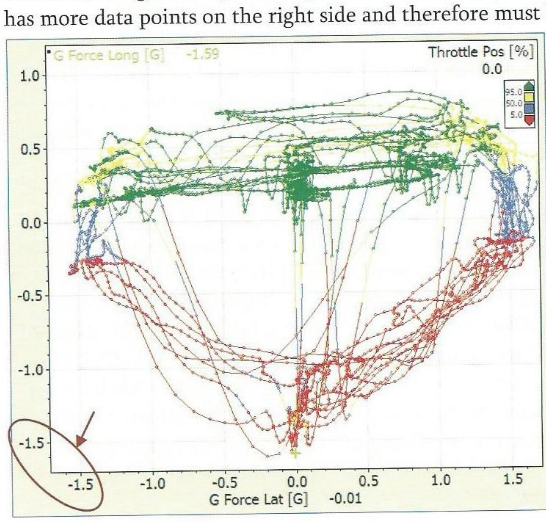

Figure 6.21 *G-G Plot with correctly filtered G forces.*

Real G-G Plot

There exist some noticeable variations from the theorized G-G Plot to a real life example. Remember to make sure the accelerometer channels have enough filtering applied to get rid of chassis and engine vibration. Notice how the top of the circle is chopped off? Most racing cars have only two driven wheels to accelerate. Therefore the car won't be able to generate as much force during acceleration as it can while braking or cornering when all four tires contribute grip. Also, the engine doesn't have enough power to break loose the driven tires while fighting aerodynamic drag. These things combine to flatten the top.

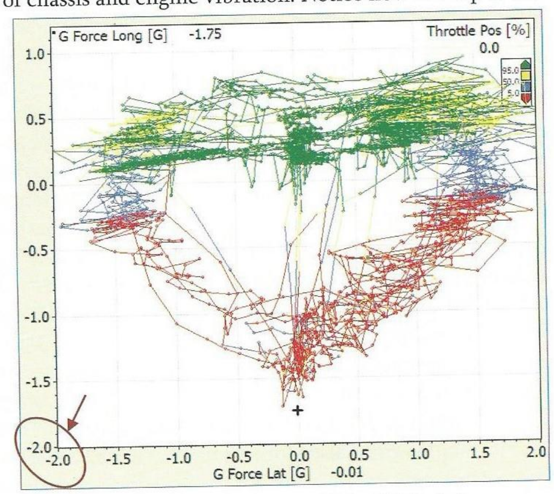

Figure 6.20 *An unfiltered G-G Plot will falsely increase the size of the traction circle, here up to 2 G's.*

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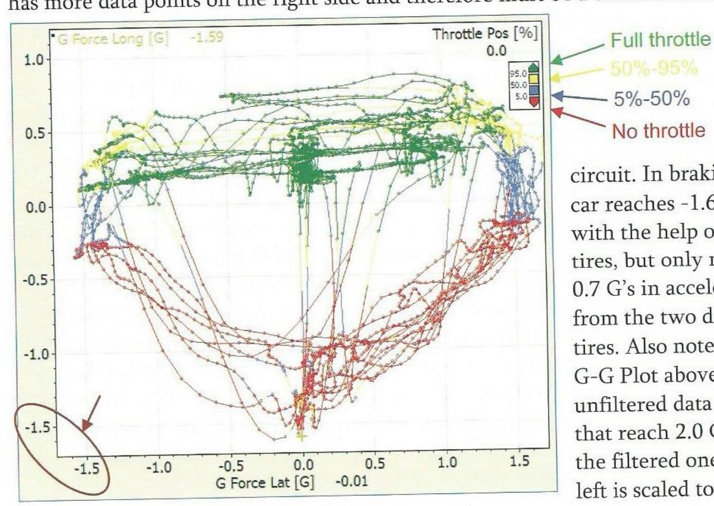


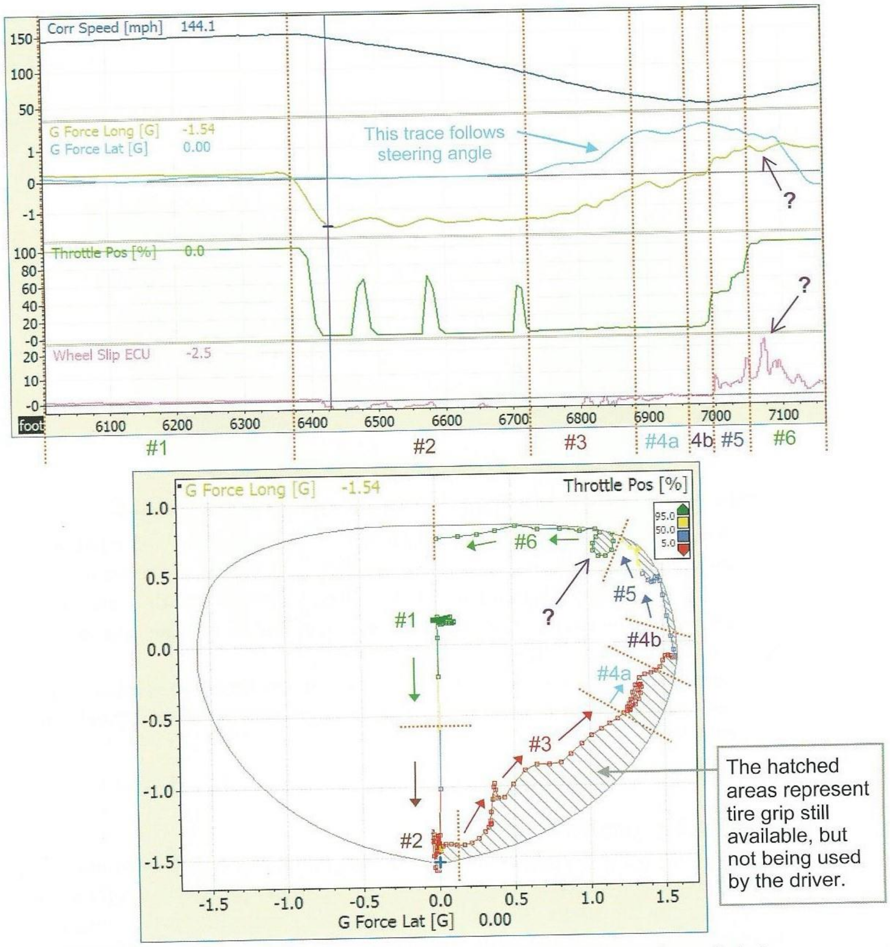
Figure 6.21 *G-G Plot with correctly filtered G forces.*

Driving the G-G Traction Circle

A theory exists in the driver's bible which states that a driver should always be pushing the race car onto the outside edge of the traction circle. Any data points not near the outer edge, represents time spent without using all of the available tire grip. In other words, the car can handle more speed than the driver is giving it.

This theory holds true for textbook type corners, Type B, but it breaks down in slow corners when followed by a long straight. In such corners a driver will be faster by braking in a straight line, turning a tighter slower radius and getting on the throttle earlier. The extra corner exit speed will carry down the straight. This extra speed will more than offset the time lost during cornering where the driver wasn't maximizing grip on the traction circle. If the straight is not long enough or if the corner is particularly fast, then a textbook driving line which requires trail braking might be faster. Exactly what a G-G diagram is good for showing. Lets take a quick tour driving around the traction circle in ***Figures 6.22***:

1. The car is at the top of the G-G plot when accelerating down a straight. There are no lateral forces and all available traction is used for acceleration. As the car reaches its top speed, the G's will slowly creep toward zero.
2. When transitioning into the braking zone, the data points move down to the bottom of the G-G Plot. Here during maximum straight line braking, all of the tire grip is used for braking and none for cornering. For high downforce cars, this maximum braking will decrease with speed as the aerodynamic forces disappear.
3. Now comes trail braking. As the driver begins to release the brakes, there becomes grip available for cornering. This allows some steering to be added. As more brake forces are released, more steering is added. If done correctly, the maximum grip of the tire is used for both braking and cornering at the same time. The curve should follow the outer edge of the circle. Anywhere it doesn't, represents tire grip that is not being utilized. While this trace is a good example, it's not perfect because it does not reach the edge of the traction circle. But a perfect trail braking trace is practically impossible. Note: This trace is dependant on the type of driving line. A slow in, fast out line will be further away from the edge.
4. Here at the center of the corner, the tires should be using up all of their available grip for cornering. In 4a, there is a large number of data points right below zero G's, which tells us the driver is not using enough balanced throttle at the apex and is either coasting or applying brake. As the driver feeds in a little throttle after the apex, G Force Long goes to zero at 4b, meaning no acceleration or braking, and all tire grip is used for cornering.
5. As the steering wheel starts to unwind coming out of the corner, grip will become available for accelerating, so throttle can be applied. This is a very good example of driving the traction circle coming out of a corner.
6. At a certain point, maximum acceleration is reached where engine power cannot break loose the tires, and therefore the throttle trace can move quickly to full throttle without worry.



Figures 6.22 *Identical data used in both the graph and XY plots above, help to illustrate the technique of driving around the G-G Traction Circle. It clearly shows a driver's skill in utilization of tire grip when trail braking.*

Always look for abnormalities in the data. In the example above, there is a drop in G Force Long at the exit of the corner where stage 6 begins. Initially one might guess this was a lift in throttle, but it can be seen in the graph where the driver never lifted. Instead, the driver attempted to exceed the traction circle with full throttle too early. It caused excessive forward tire slip resulting in a loss of traction and therefore a loss in forward acceleration as seen in the data. In this example, Wheel Slip ECU is calculated from the individual wheel speed channels and graphed. This is a good example of how an XP plot can more easily show certain problem areas, but how squiggly lines cannot be ignored in the analysis as they tell more of the story.

Chapter 7 Steering

Steering angle can be defined in two different ways. One is the angle of the steering wheel known as "steering wheel angle". The other would be "steered angle" which represents the angle of the tires to the car.

Figure 7.1 *Steering Wheel Angle*

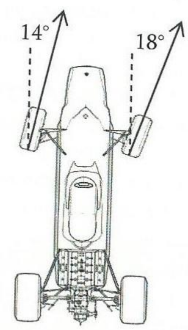


Figure 7.2 *Steered Angle*

Steering wheel angle is often easier to understand because of the relation to the visual angle of the steering wheel which a driver sees. It is also easier to calibrate. But steered angle is more useful for vehicle dynamics equations and is more preferred by the engineer. These equations can calculate the handling of the car and confirm or substitute feedback from the driver.

Since these two channels are directly connected to the same steering rack and mechanism, there will be a direct correlation so it becomes easy to log one and calculate the other.

7.1 Steering Calibration

Calibrating Steering Wheel Angle

For steering wheel angle, the calibration is simple and would consist of calibration angles every 90° as seen in ***Table 7.1***. The angle can be set by sight alone, without any additional tools. Being off by 2° out of 90° is only a 2% error. Most basic analysis and comparisons with respect to steering require greater differences, so accuracy isn't very important with regard to this channel. Standard convention is to use the same sign convention as G Force Lat. Therefore when turning both G Force Lat and steering move in the same direction.

Calibration table

V	deg
1.000	-180.0
1.600	-90.0
2.500	0.0
3.400	90.0
4.000	180.0

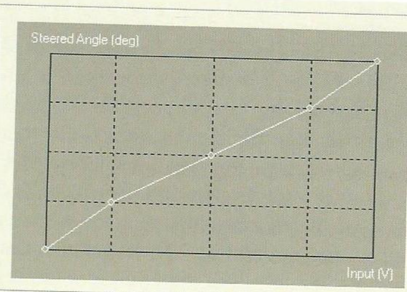


Table 7.1 *Calibration for Steering Wheel Angle.*

Calibrating Steering Wheel Angle

For steered angle many more points are needed in order to obtain enough accuracy for the calibration. This is especially true when doing any math channels with the steered angle channel. It is easiest to calibrate with a set of turn plates, which accurately measure wheel angle with respect to the car.

Figure 7.3 *Turn plates are mechanical platforms sitting on bearings which allow pivoting of the tire. This is used to accurately measure steered angle.*

When a vehicle turns a corner, the inside tire travels a tighter radius than the outside. Therefore the tire needs more steering angle than the outer wheel. Many steering systems are designed as such, known as the steering Ackermann effect. Most street cars will use normal Ackermann where the inner tire turns with more angle than the outer tire. But race cars spend more time cornering at higher G loads, so they are designed with varying levels of Ackermann to optimize grip from each tire slip angle. Some cars will have anti-Ackermann where the inner tire turns less angle than the outer tire. Such designs can be seen on a current Formula One car. So when creating a single steering channel, which tire should we measure?

The most accurate answer would be to calibrate separate right and left steered angle channels and average the two based on the amount of weight each tire is carrying. That would require suspension load sensors. Luckily that level of sophistication isn't needed for our topics covered in this book.

When a car turns through a corner, its weight is transferred from the inside tire to the outside tire. The outside tire will therefore make the largest contribution to the direction or turning arc of the car. It dictates where the car goes. Depending on G forces, the outside tire might carry up to 80% or 90% of the total front tire load. The inner tire is mostly along for the ride, contributing very little to the steering forces being generated by the front tires.

Therefore steered angle should measure the angle of the outside tire. This will generate results within an acceptable margin of error for most analysis needs. When turning right, steered angle is the left tire angle. When turning left, steered angle is the right tire angle. A typical calibration for steering wheel angle is shown in ***Table 7.2***. The accuracy of steered angle is more important than steering wheel angle because steered angle is often used in vehicle dynamic equations and is a much smaller number. Steering wheel angle is mainly used as a driver reference. Steering geometry is mostly linear (straight line) through most of its range, with some possible non linear sections near the physical limits of steering.

Calibration table

V	deg
1.000	-12.0
1.300	-8.0
1.600	-6.0
1.900	-4.0
2.170	-2.0
2.500	0.0
2.830	2.0
3.100	4.0
3.400	6.0
3.700	8.0
4.000	12.0
1.120	-10.0

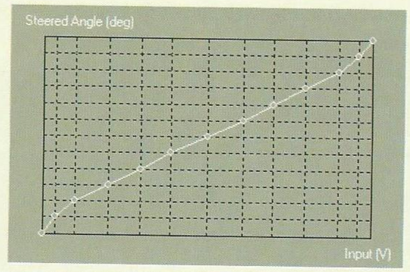


Table 7.2 *The calibration for Steered Angle requires many more points at smaller increments to maintain accuracy*

If the steering sensor has been calibrated for steered angle, it is relatively easy to convert that channel into steering wheel angle. This can be done with a scaling factor or in a 2D table which converts through linear interpolation.

Channels

Input Channel : Steered Angle — Select...

Output Channel : Steering Wheel Angle — Select...

Table

Number	deg	deg
1	-12.3	-180.0
2	-5.6	-90.0
3	0.0	0.0
4	5.7	90.0
5	12.2	180.0
6		
7		

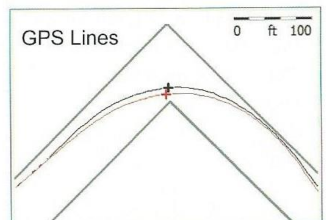
Table 7.3 *Table to convert Steered Angle into Steering Wheel Angle.*

7.2 Line Analysis

One of the first uses for steering during analysis is to locate the turn in point for a corner. The turn in point helps define the driven line and can be extremely valuable when comparing different drivers. When traveling down a straight, the steering trace should rest near 0°. The point where this line first starts to move up or down away from zero indicates the turn in point. When comparing different laps, this will be the first clue to determining how different lines are being driven through the corner.

After the turn in point, take a look at the amount of steering input, which is proportional to the radius of turning. In fact with both steered angle and speed channels the actual radius can be calculated. Things to look for when analyzing the driven line through a corner are:

1. Turn in point
2. Rate of turn in
3. Amount of maximum steering angle
4. Release of steering angle
5. Throttle application on the exit



These five things define the driven line. But only with the variance channel can you put a time advantage on one line over the other.

In the next example of ***Figure 7.4***, two laps are driven around a 90° corner typical of street circuits. The steering trace shows the red line turned in earlier and with less maximum steering it generated a higher minimum speed. Typical of a textbook racing line. The black trace braked later, harder and had a lower minimum speed with a tighter radius. Typical of a late apex line where the black trace was able to get onto the throttle earlier. But here is where the value of GPS comes in. The black line wasn't a late apex line, but rather an overshot corner where the driver missed the apex by 10 feet. This line required a tighter radius with more steering. If the black trace was a late apex line, then the maximum steering would have been located earlier than the maximum steering of the textbook line in red. But the red trace wasn't perfect either. You can see the release of steered angle where the driver had to correct for turning in too much too early. According to the variance, the higher minimum speed of the red trace more than made up for the late braking, but eventually lost that time advantage by the earlier throttle of the black trace. The truth is in the variance channel.

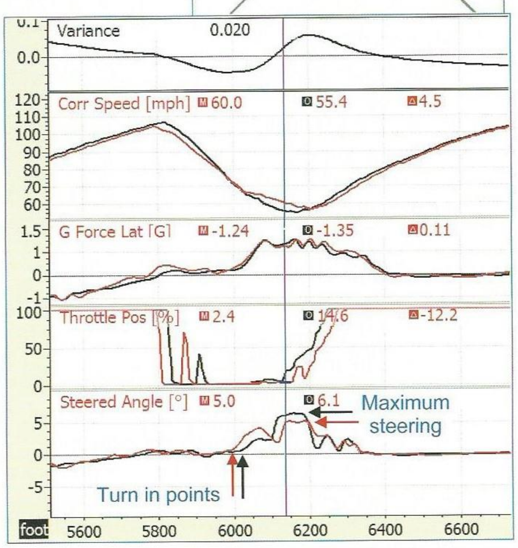


Figure 7.4 *Finding variations in driven lines around a corner starts with steered angle.*

The limitations of using only the channel G Force Lat are seen here where practically no differences are shown between the laps. This proves the importance of having logged a steering channel in addition to G Force Lat.

7.3 Car Handling Oversteer/Understeer

Professional drivers are experts at extracting all of the available grip from a tire. This is how they go fast and keep their jobs. As described in the traction circle theory, getting the most out of the tire requires driving on the outer edge of the traction circle. No where is this more evident than when trail braking. To drive on the outer edge requires an understanding of how a tire operates near its grip limit. This is governed by a tire curve. The tire curve defines the maximum grip available from that tire, and is based on the slip angle of the tire. Tire grip builds with slip angle up to its optimal peak. Asking the tire to provide more grip generates slip angles past its peak, and overall grip decreases. This peak in the tire curve is also the limit of the traction circle because the tire simply can't generate any additional grip.

Figure 7.5 *Tire grip curves for different types of tires.*

Examples of a tire grip curve is shown in ***Figure 7.5*** above. The curve depends on many factors such as the chemical makeup of the rubber compound, construction method and size of the tire. Street tires have a much different curve than racing tires. They are flat and wide at the top, with minimal drop in grip after their peak. A racing tire is the opposite, featuring a narrow peak for more maximum grip but a dramatic drop after its peak. Feeling when the tire is at its optimal slip angle and not driving past that point can be a very difficult thing to feel. From a drivers training perspective, being on a street tire allows them to push the limits and keep the tire on its peak. Only small changes in grip are experienced when exceeding that peak. This is much safer than a racing tire which has drastic consequences for exceeding the limit.

A car not driven fast enough will never reach the outer edge of the traction circle, nor the peak grip of the tire. The race car will never exhibit bad handling because its not being driven fast enough. When a driver speeds up and attempts to go past the traction circle (tire peak), grip drops off and the car is forced to slow down. Rarely will the balance be so perfect that all four tires slide at the same time. Rather one end, either front or rear, will lose grip first. When this happens, the car becomes unbalanced and can't go any faster. The *balance* of the race car is often described by the driver with two words, *oversteer* or *understeer* depending on which end of the car loses traction first.

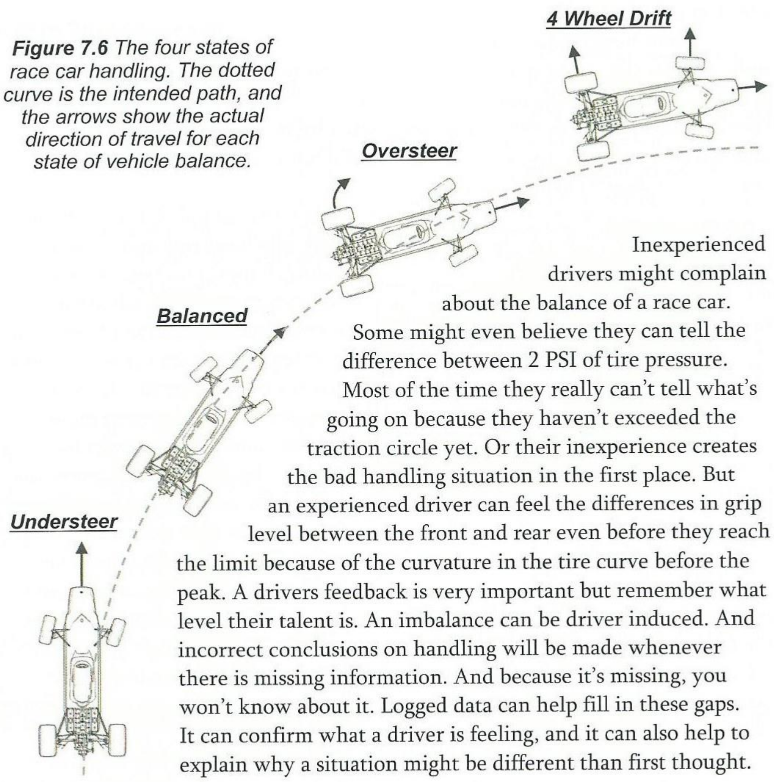


***Figure 7.6** The four states of race car handling. The dotted curve is the intended path, and the arrows show the actual direction of travel for each state of vehicle balance.*

Inexperienced drivers might complain about the balance of a race car. Some might even believe they can tell the difference between 2 PSI of tire pressure. Most of the time they really can't tell what's going on because they haven't exceeded the traction circle yet. Or their inexperience creates the bad handling situation in the first place. But an experienced driver can feel the differences in grip level between the front and rear even before they reach the limit because of the curvature in the tire curve before the peak. A drivers feedback is very important but remember what level their talent is. An imbalance can be driver induced. And incorrect conclusions on handling will be made whenever there is missing information. And because it's missing, you won't know about it. Logged data can help fill in these gaps. It can confirm what a driver is feeling, and it can also help to explain why a situation might be different than first thought.

What is Oversteer?

Most drivers prefer to go forward rather than backwards, hence they complain when the rear of the car slides sideways or spins around. When the rear tires lose traction, we call this oversteer. Also known as being *loose*, this situation is easily identified even by a novice driver. To correct this imbalance, the natural reaction of the driver is to reduce the steering angle and sometimes even steer in the opposite direction of the corner. Adding front grip makes this problem worse.

These steering corrections are evidence of oversteer, and are one of the quickest things to spot on a steering trace. But the effect of oversteer on the G Force Lat will depend on where the accelerometer is located. When a car oversteers, it pivots about the front tires as the rear tires exceed their peak grip level and begin to slide. An accelerometer mounted at the rear of the car will measure less G force. If the accelerometer is located in front, say between the front axles, it will remain level. If the oversteer gets severe and the driver runs out of talent, then G Force Lat drops to zero as the car spins, no matter where its located. An accelerometer mounted in the middle, or close to the center of gravity, will still decrease during oversteer, but not as much as one mounted in the rear.

What is Understeer?

Understeer happens when the front tires of the car lose grip and starts to slide. The car simply *pushes* forward instead of turning. Contrary to an oversteer situation, a car that understeers does not make any sudden changes in direction. Hence an inexperienced driver will have difficulty in knowing the car has understeer. For the engineer it is also more difficult to identify as it requires analysis of multiple channels of data.

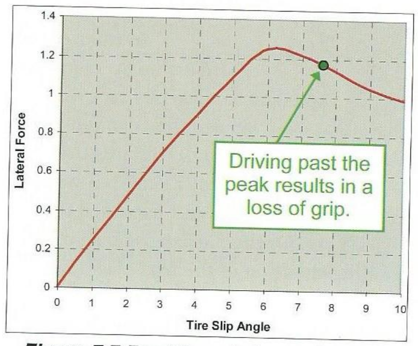


Figure 7.7 Front tires during understeer.

When the front tires exceed their peak grip level and start to slide, the vehicle exhibits understeer. And contrary to oversteer where the natural human reaction of reducing steering angle is the correct response, when a car understeers the natural human reaction is to steer more. Adding more steering angle increases the tire slip angle, which causes the tire to lose more grip as it continues down on the back side of the tire grip curve. This makes the understeer even worse! The drop in grip from additional steering can have a small effect or drastic effect, depending on the tire slip angle curve. The wider peak of a street tire still provides enough grip to keep the car turning, even if the slip angle exceeds the peak. This makes understeer much more forgiving than a racing tire which can cause the race car to stop turning altogether.

Not only is it harder to realize when understeer happens, the required correction doesn't come naturally. It takes skill and training to master. Professional drivers identify understeer quickly when the car stops responding to additional steering input, and by feeling the drop in steering torque. Due to the shape of the tire grip curve once a car starts to understeer, releasing the steering can actually provide more grip! Reducing the steering angle reduces the slip angle and moves the car back onto the peak of the tire grip curve. It goes against the natural reaction of most drivers, but for a professional racing driver it becomes second nature.

To the detriment of enthusiast drivers around the world, most newer street cars now have strong power steering systems which remove most of the feedback forces coming back through the steering wheel. Feeling the steering torque generated at the tires is now next to impossible. Another reason why inexperienced drivers rarely get a grip on understeer.

4 Wheel Drift?

While this state is possible to achieve, it is very rare on most on-road circuits. You might encounter this on gravel or iced roads, anywhere that traction is difficult to find. The four wheel drift is technically a balanced state with the vehicle sliding on both the front and rear equally.

How to Find Oversteer

Oversteer is found by a reduction in steering angle or reversal of steering direction. Two steering corrections were made in ***Figure 7.8***. The cursor is located on the first steering correction near the exit of the Keyhole at Mid-Ohio. The driver corrected by reducing the steered angle from 5° all the way to 0°, then back to 4° to finish out the corner. In most oversteer situations, and depending on where the accelerometer is mounted, the G Force Lat channel will decrease during oversteer then increases again after the correction. Then G Force Lat finally falls back down as the driver unwinds the steering wheel back to zero.

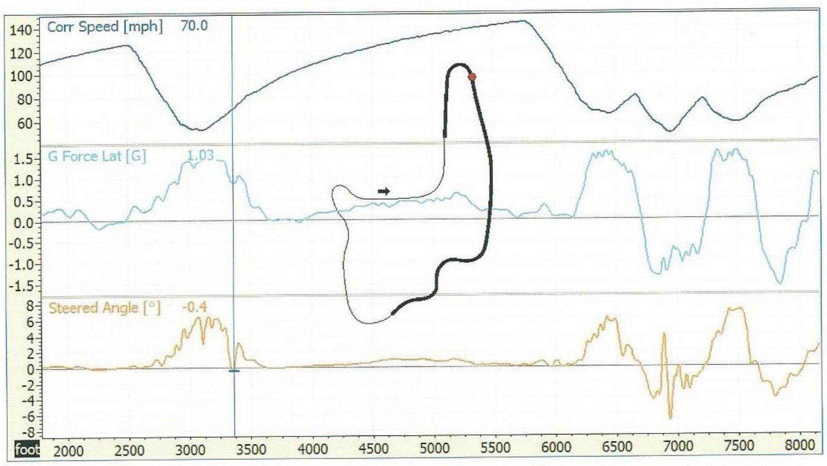


Figure 7.8 *There are two oversteer corrections on this lap. Can you find both?*

A larger correction occurs just before a lap distance of 7000 feet. Here the steered angle goes from -4° to +4°, which ended up being too much of a correction. So the driver flips the wheel to -7° then to 0° for another correction before finally getting back to -3° to finish out the corner. The G Force Lat value decreased from 1.3 Gs before the correction to right under 1.0 Gs for a decrease of around 30%.

Some racers refer to these repetitive corrections as a *tank slapper*. The term originated with motorcycle riding when a steering wobble would cause the handle bars to slap against both sides of the gas tank one after another. It almost always ended with a crash. When a vehicle exhibits oversteer, the driver must correct the proper amount at the proper time. Over correction and delayed reactions are a sure recipe for tank slappers. Sometimes the suspension settings, specifically flexible kinematic joints in the rear toe control of production cars can also contribute to this phenomena.

Oversteer is commonly caused by too much throttle. It can also happen if the car bottoms out or has poor suspension geometry where the tires are allowed to lean past their optimal camber angle.

An example of throttle induced oversteer is shown in ***Figure 7.9***. A steering correction was made and the G Force Lat value decreases as expected. It all went bad the moment this driver got on the throttle. The driver pause throttle application and waited to apply more until the correction was effective in stopping the oversteer imbalance.

With ***Figure 7.10***, notice how great the timing of the oversteer correction was to the application of throttle. Just to the right of the cursor, the shape of the steering almost matches exactly the shape of the throttle. Drivers have the ability to anticipate situations based on experience. This anticipation is an important skill in driving race cars. Inexperienced drivers often lift off the throttle because they don't have the confidence that a steering correction will sort things out.

In some situations, lifting off the throttle makes the oversteer worse due to weight transfer from the rear to the front. Less weight on the rear equals less traction on the rear. One of the advantages to an ideal throttle application is the ability to transfer some weight back onto the rear tires. This weight aids in the tire grip to handle even more engine power. In ***Figure 7.10***, the balanced throttle and smooth tip in, allows for some weight transfer to occur. Lifting would in this case make the oversteer worse. But in ***Figure 7.9***, where there was no balanced throttle or a proper initial throttle, weight transfer didn't happen and the engine simply overpowered the available traction. Lifting or delaying throttle would be the proper response, but a balanced throttle might have avoided this situation entirely.

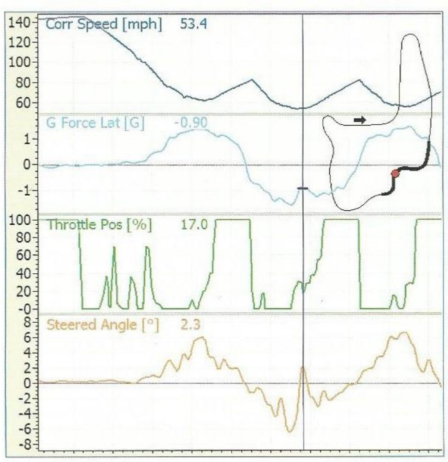


Figure 7.9 *Oversteer caused by throttle.*

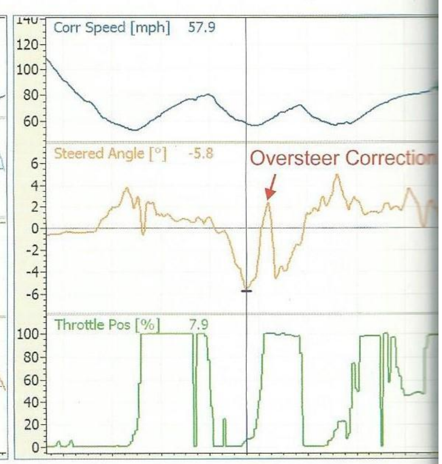


Figure 7.10 *More throttle induced oversteer.*

How to Find Understeer

Unlike oversteer, understeer cannot be found from steering alone. It requires additional channels of G Force Lat and Speed. That's because all three of those channels are related through a fundamental equation of motion which governs a body in a circular path. The equation is as follows:

$\omega = \upsilon^2 / r$ angular acceleration = velocity squared / radius

Rearranging that equation and putting in motorsport terms, we end up with a simple equation for angular acceleration which states:

G Force Lat = Speed^2 * (tan (Steered Angle) / (-1 * Wheelbase))

This equation is simplified in that it ignores tire slip angles. Therefore it is not exact, but is still the foundation for determining understeer. The following conclusions can be made from this equation:

1. If **Speed** increases, so must **G Force Lat**, unless **Steered Angle** is decreased. In other words, to accelerate out of a corner a driver must reduce steering angle in order to accelerate.
2. If **Steered Angle** increases, so must **G Force Lat**, unless **Speed** is decreased. In other words, to enter a corner a driver must reduce speed when adding steering angle.

The last one is most important for finding understeer. To repeat the second conclusion from above in a different way:

2. If **G Force Lat** remains constant and **Speed** remains constant or is increasing, any increase in **Steered Angle** indicates understeer.

In the most simplified way, it states an increase in steering angle should also increase lateral G forces. Anywhere that doesn't happen the vehicle has understeer.

△ Warning: A common mistake is to forget that speed is also included in the equation of motion. To claim an increase in steering angle should increase lateral Gs, is only true as long as speed is not decreasing.

When the maximum slip angle has been exceeded in a corner, lateral G force will either stay flat or drop off, depending on the shape of the tire grip curve. In ***Figure 7.11*** the period from the cursor shows an increase in steering angle, with speed relatively constant near its minimum and lateral G force dropping. This is a sure sign of understeer. The understeer starts in the middle of the corner, so don't confuse this with exit understeer.

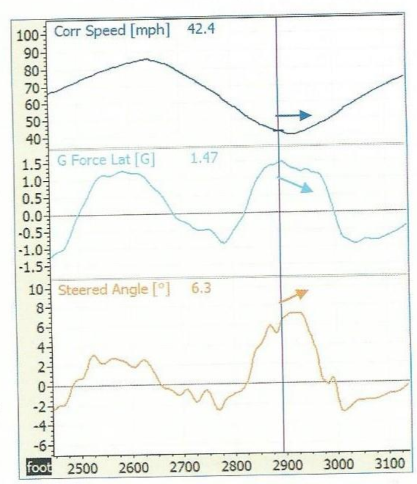


Figure 7.11 *Understeer as Steered Angle increases and G Force Lat falls off.*

When understeer happens at the exit of a corner the driver runs out of useable pavement very quickly. Understeer in the middle of the corner can also cause this, but there should be time to adjust while exiting before running out of room. So many drivers will accidentally misdiagnose the problem and complain of exit understeer rather than mid-corner understeer. It takes an experienced driver to discern the differences, or some valid data to prove where it started.

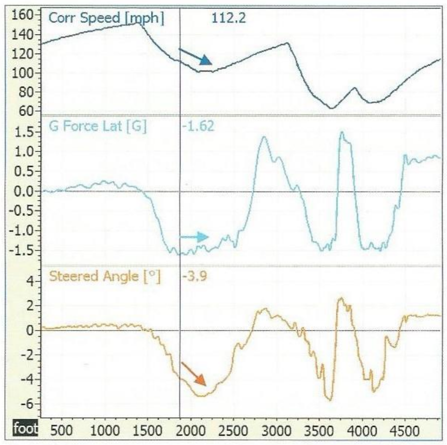


Figure 7.12 *Steered Angle increases, G Force Lat remains flat, is this understeer?*

Using the example in ***Figure 7.12***, steered angle is continually increased after the cursor while G Force Lat reaches a plateau earlier. At first glace this looks like understeer, but notice the rate at which speed continues to decrease. This is not understeer because the rate of speed decreasing offsets the amount of steering added. This is typical of long decreasing radius corners. Both speed and steering decrease together and the balanced car generates a plateau in G force.

Understeer should be categorized by where it starts either in corner entry, middle or exit. This is imperative when deciding how to correct the balance problem. Understeer which starts in a corner exit phase might be caused by weight transfer. When accelerating, weight is moved off the front and onto the rear tires. Therefore decreasing front grip and increasing rear grip. While that's great for accelerating, it's not for turning. When this happens, the driver resists the natural unwinding of the steering wheel while exiting the corner, and are eventually forced to lift off the throttle.

△ *Warning:* Be extra careful when analyzing understeer in banked corners. Any amount of banking on a corner, positive or negative, will cause errors in the accelerometer measurement due to gravity. This increases the difficulty in understanding what is truly happening to the balance of the race car.

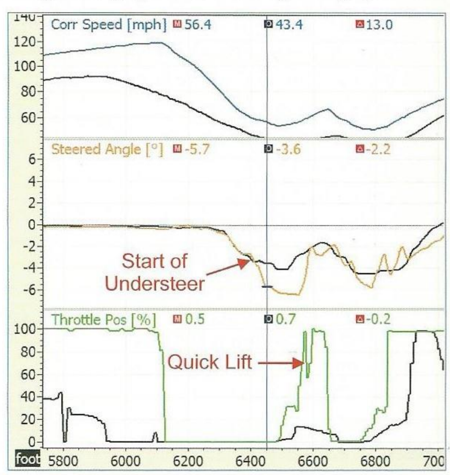


Figure 7.13 *Typical oversteer in the middle of a corner made worse by throttle application.*

Steering Reference Lap

The quickest way to determine oversteer and understeer is to have a steering reference lap overlaid. A lap which is ideal in driving line, but only driven at 8/10ths the speed. This will guarantee tire slip angles don't go past their peak. The lap will have no oversteer and no understeer, hence this lap will be called the *steering reference lap*. When overlaid with a lap at speed, or 10/10ths, it will be very quick and easy to spot oversteer and understeer.

The graph in ***Figure 7.13*** shows understeer which started just before the cursor, half way between corner entry and the middle of the corner. This can be spotted with help from the steering reference lap. A tried eye could also spot this with the location that G Force Lat falls off. Notice how the steering angle stayed at -6 deg all through the corner and how the driver had to lift off the throttle at the exit of the corner. This is severe understeer and happened on a street circuit where grip was lacking on the concrete.

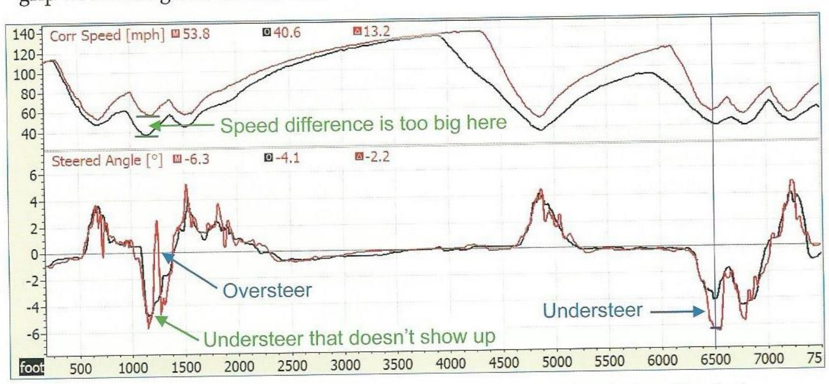


Figure 7.14 *A steering reference lap can be very helpful to locate handling balance problems. Notice the lap is driven slower as to not exceed tire grip levels.*

Another good example of using the steering reference lap is shown in ***Figure 7.14***. The reference overlay makes it very clear when the understeer begins. It also helps relate the severity based on how far apart the two steering traces are.

Note: Only areas with large differences are of interest. Small variations are within the margin of error from this estimation.

△ *Warning:* Driving too slowly, perhaps even 7/10ths the normal speed, will exaggerate the necessary steering angle required to negotiate a corner due to the larger steering angles required at slower speeds. This will create areas that look fine, when in fact there exists understeer. Around the 1100 foot mark in ***Figure 7.14*** is a prime example. Therefore keep the car just slow enough to prevent any unbalance from tire slip angels.

Steering Calculated

While the steering reference lap is an excellent resource to use, sometimes it becomes a pain to keep opening and overlaying a lap out of a different file. There is another method, albeit more complicated and potentially more error prone.

Going back to that fundamental equation of motion which governs a body in a circular path from page 119,

$\omega = u^2 / r$ angular acceleration = velocity squared / radius

and rearranging that equation with motorsport terms, we end up with:

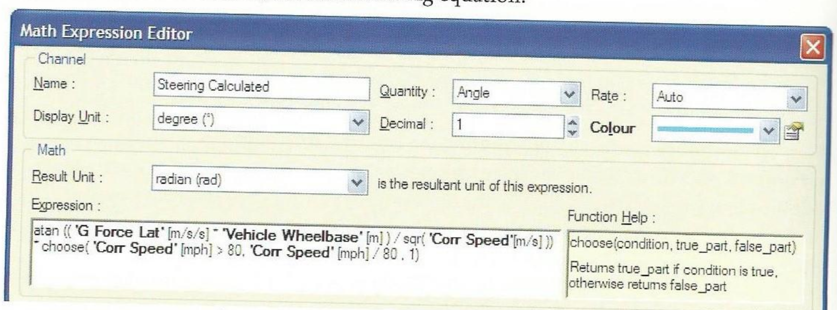
G Force Lat = Speed^2 * (tan (Steered Angle) / (-1 * Wheelbase))

and rearranging that equation to solve for steering gives:

Steering Calculated = arctan (G Force Lat * Wheelbase / Speed^2)

Which is an equation for "Steering Calculated". Or in other words, *what the steering angle should have been rather than what the drive did.*

Remember that this equation does not take into consideration slip angles. To improve this estimate, an adjustment based off the speed channel should be added. Some people refer to this as speed weighted and it helps take into effect the added slip angles induced when traveling at faster speeds. If the speed is higher than "X" mph, multiple the result by (Speed / "X"). If the result is less than "X" mph then no additional factor is needed. The "X" will be some value between 40 to 80 mph. The exact number depends on the tire, track surface and the car itself, so some experimentation will be needed to find the best value. Try 40, 60, and 80 mph to see what gives the best result. The exact equation will vary based on your analysis software. For MoTeC's i2, use the following equation:



This added correction makes the channel more accurate at higher speeds. Even with any chosen amount of "X" factor, the oversteer and understeer can still be clearly seen in ***Figure 7.15***.

△ Warning: This equation falls apart and should not be used if any of the following conditions apply:

- Banked corners as the G Force Lat sensor reads gravity.
- Steered Angle not reading 0 when going straight (oval racers).
- Steered Angle not calibrated correctly or calibrated for steering wheel angle.

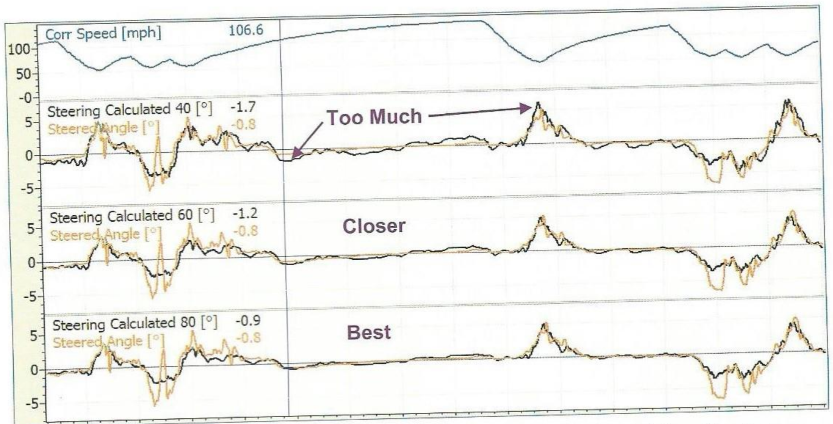


Figure 7.15 *Comparing three different "X" values for speed weighting, it's clear that 80 mph generates the best Steering Calculated curve for this car.*

Looking at ***Figure 7.16***, compare this graph to the steering reference lap of ***Figure 7.14***. Notice how the steering calculated channel correctly identifies understeer around 1100 feet. This was absent in the steering reference lap because that reference lap was driven too slow in that one corner. Steering calculated is based off the lateral G forces for the lap being analyzed, so it can often provide better results. Remember to discuss any questionable areas of car handling and balance with the driver. Then use the data to reinforce the driver feedback, or to fill in any missing information.

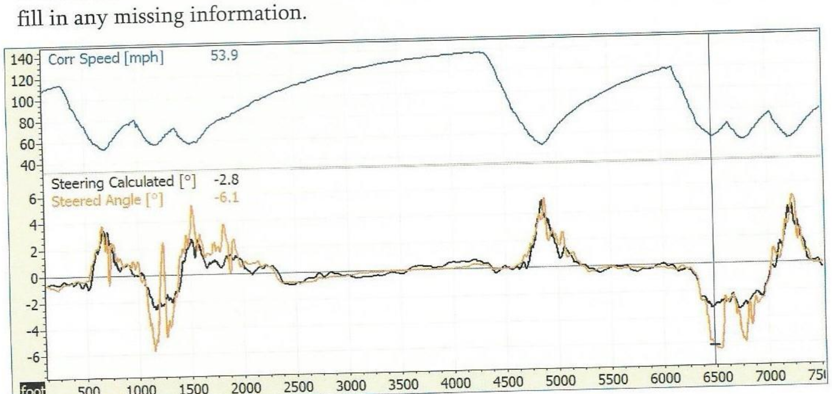


Figure 7.16 *Here's what a proper Steering Calculated curve looks like behind the driver's Steered Angle. Compare this to the steering reference lap in Figure 7.14.*

Note: Only areas with large differences are of interest. Small variations are within the margin of error from this estimation.

Chapter 8 Track Mapping

Track Map Generation

If your data system does not use GPS, then track maps are generated from three items; Beacon, Speed and G Force Lat. The beacon defines where a lap starts and stops. The speed channel is integrated to calculate lap distance. And finally speed combined with lateral G forces generate the corner radius. Track maps will be drawn incorrectly if problems occur with any one of those three channels.

The math behind this track map generation does have errors and therefore the end of the lap does not line up exactly where the lap started. These errors are due to many factors including:

- inaccuracies in speed which effect the length of the lap
- tire slip angle / car sliding which effects the corner radius
- lateral G force errors due to vehicle roll during cornering

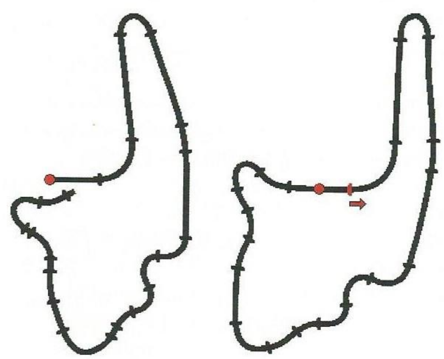


Figure 8.1 *Open circuit versus closed circuit.*

Because of these effects, track maps must be specified as *open* or *closed* in the analysis software. Rally circuits or autocross events are good examples of an open circuit where the finish line is not at the same location as the starting line. When chosen to be a closed circuit, the difference between the end and start is mathematically averaged across every point along the track. This forces the end to line up and connect to the start and form a closed circuit.

Once connected, the track map might still not look correct. A good example of this would be a track map of the road coarse at Daytona International Speedway. This track has large banking angles on the oval portion, which causes the accelerometer to include gravity in its measurement of lateral G force. The track pictured below on the left is a map generated from Beacon, Speed and G Force Lat. On the right is one drawn from GPS positional data. Street circuits are also problematic as the tall buildings can block GPS signals, resulting in a worse track map than one created from Beacon, Speed and G Force Lat.

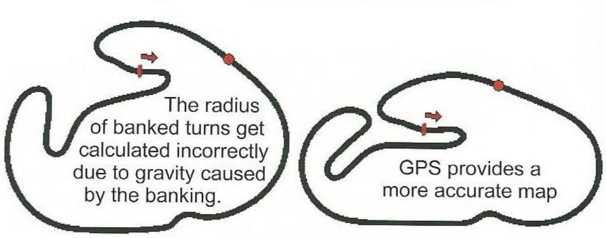


Figure 8.2 *Daytona track map based on lateral G versus GPS.*

Beacon Location

Lap timing is accomplished with a transmitter on the side of the track and a receiver inside the car. As the car passes the transmitter, the receiver triggers off the infrared light to mark the start of a lap in the data. In ***Figure 8.3*** the transmitter is sitting on top of a tripod.

On the Daytona map in ***Figure 8.2***, the red section marker represents where the beacon transmitter was placed. The arrow shows the direction of travel. The red dot shows where the official start/finish line is located. Although it would be ideal to place the beacon transmitter at the start / finish, this is not always possible. Some racing series have their own timing and scoring systems in this area and forbid objects in their way. There will also be a plethora of beacon transmitters from all the teams vying for the same spot. The most important thing is to place the beacon transmitter at the same spot every time you visit a track. This will result in data which always lines up correctly with previous data from prior years.

Figure 8.3 *Along the track sits the beacon transmitter onto a tripod stand.*

Check to see if your analysis software has a beacon shift function, something that allows you to shift the location of the beacon after logging. This is important if you are forced to move the location of the beacon transmitter.

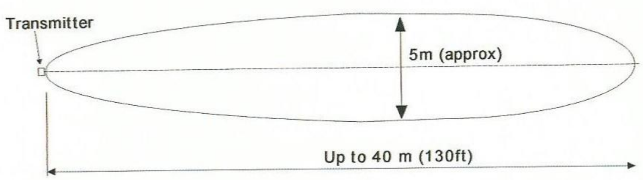


Figure 8.4 *The beacon transmitter sends out a cone shaped signal.*

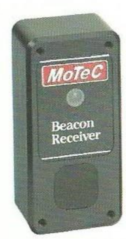


Figure 8.5 *The beacon receiver sits inside the car.*

△ Warning: Do not place transmitters next to each other. As their output forms a cone, two transmitters close together will interfere with each other by overlapping their pulses of light.

△ Warning: The beacon transmitter must be placed at the same spot along the track every time. Keep a list of beacon locations for each track both written and with pictures. If the transmitter must be moved to a new location, the data must be shifted in order to analyze the new data with the old data.

Defining Sections

The track map should be divided into sections such as corners and straights. Many times these are auto-generated based on some value of lateral G force which defines when the car is cornering versus traveling down a straight. All data systems should allow manual adjustment of these sections. Many tracks will have small and short corners often called *kinks*, which get ignored because the lateral G force is not high enough for the auto-generated sections. In the Mid-Ohio example, Turn 3 is completely ignored by the auto-generated sections. Therefore it's best to change the default sections to match that of the official track map. Many drivers and coaches use the official turn numbering or names when instructing and discussing the track.

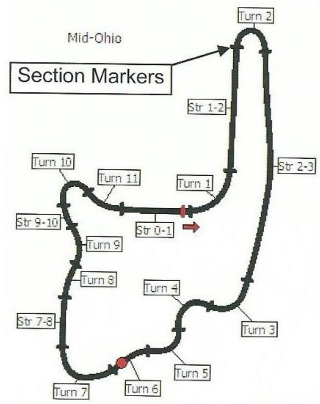


Figure 8.6 *Auto-generated sections.*

Figure 8.7 *Official Pro sections.*

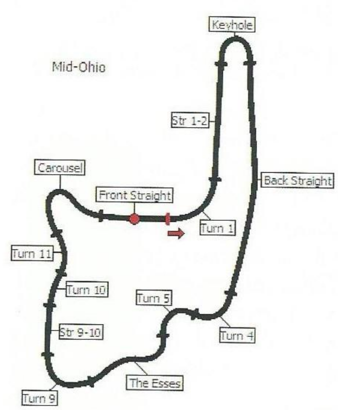


Figure 8.8 *Analysis sections can be easier to work with.*

Outside North America, most tracks use names rather than numbers for their turns. Therefore rename as needed. In the Mid-Ohio example, Turns 12 and 13 might be combined to form the more common name *Carousel*. Turn 2 becomes the *Keyhole*. Turn 3 should be removed and the entire straight labeled *Back Straight*. This group will be referred to as the "Analysis Sections" shown in ***Figure 8.8***. Sections are also used to label areas on a graph for easy reference. Below is an example graph of Mid-Ohio using the "Analysis Sections" along the top of the graph.

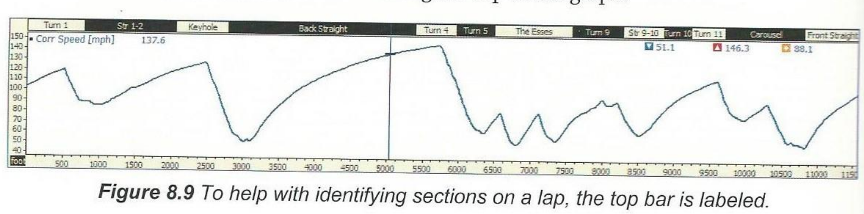


Figure 8.9 *To help with identifying sections on a lap, the top bar is labeled.*

GPS Track Maps

If GPS positional data is being logged, then it can produce great images of the driving line, as long as the quality of the GPS doesn't suffer any signal drop outs around the track. Many data systems allow for mapping of the inner and outer edges of the track as well. This is accomplished by driving along the edge with the race car or a golf cart outfitted with the same data logger used in the race car. It adds another element to visual training and can make driving lines easier to comprehend.

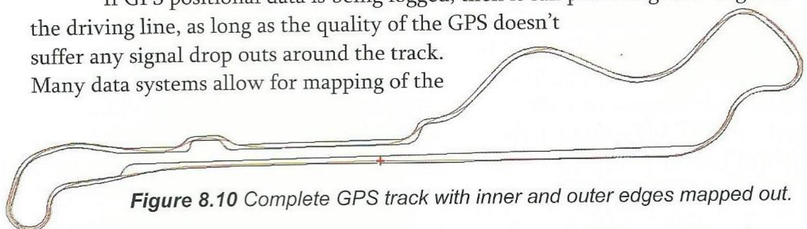


Figure 8.10 *Complete GPS track with inner and outer edges mapped out.*

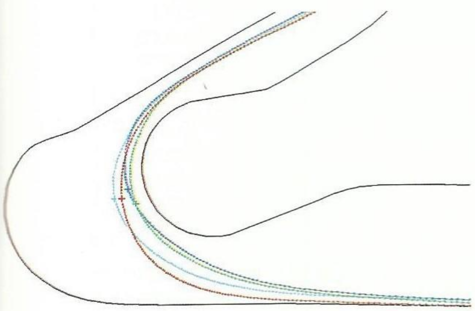


Figure 8.11 *Analyzing driving lines is much more visual if there is a width defined by the outer and inner edges of the race track.*

△ Warning: When analyzing driving lines via GPS data, please be aware that a shift in position might occur. The shift can change throughout the day, but should be unnoticeable during short time periods such as a 30 minute session. It might be noticeable comparing afternoon to morning data. Hopefully your data system can shift each downloaded data file separately if required. This is not typically needed if you have quality GPS satellite coverage.

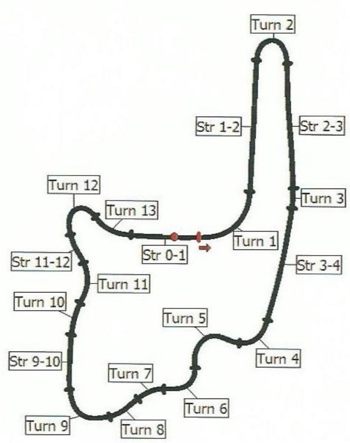
Figure 8.12 *Here the black trace needs to be shifted down and to the left by ~ 20 feet.*

Chapter 9 Section Timing

Most data analysis software programs are able to provide something called *Section Timing*. Most racing teams record lap times for each session, usually written down by someone with a stop watch. Section Timing is similar, only imagine having a stop watch before and after every corner. This function reports in a table format, the time it took the race car to complete each section of every lap. For example, how long did it take to drive through a particular corner or down the main straight?

	Mid-Ohio						Eclectic	Rolling Minimum
	Lap 1	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6		
Turn 1	0:05.188	0:05.245	0:05.169	0:05.127	0:05.141	0:05.112	0:05.112	0:05.127
Str 1-2	0:09.363	0:09.333	0:09.288	0:09.278	0:09.324	0:09.239	0:09.239	0:09.278
Turn 2	0:03.787	0:03.712	0:03.872	0:03.787	0:03.986	0:03.783	0:03.712	0:03.787
Str 2-3	0:11.505	0:11.652	0:11.744	0:11.572	0:11.972	0:11.529	0:11.505	0:11.572
Turn 3	0:01.239	0:01.246	0:01.241	0:01.239	0:01.245	0:01.239	0:01.239	0:01.239
Str 3-4	0:06.066	0:06.111	0:06.071	0:06.085	0:06.097	0:06.058	0:06.058	0:06.085
Turn 4	0:02.074	0:02.117	0:02.051	0:02.052	0:02.228	0:02.095	0:02.051	0:02.052
Turn 5	0:06.129	0:05.982	0:06.139	0:06.070	0:06.786	0:06.090	0:05.982	0:06.070
Turn 6	0:05.087	0:05.120	0:05.119	0:05.173	0:05.363	0:05.175	0:05.087	0:05.173
Turn 7	0:02.916	0:02.886	0:03.003	0:02.985	0:02.941	0:02.878	0:02.878	0:02.985
Turn 8	0:03.678	0:03.645	0:03.622	0:03.567	0:03.863	0:03.753	0:03.567	0:03.567
Turn 9	0:04.602	0:04.617	0:04.558	0:04.602	0:04.897	0:04.606	0:04.558	0:04.558
Str 9-10	0:05.425	0:05.555	0:05.465	0:05.483	0:05.523	0:05.557	0:05.425	0:05.465
Turn 10	0:02.566	0:02.587	0:02.540	0:02.550	0:02.540	0:02.534	0:02.534	0:02.540
Turn 11	0:02.712	0:02.730	0:02.704	0:02.697	0:02.704	0:02.704	0:02.697	0:02.704
Str 11-12	0:02.294	0:02.283	0:02.331	0:02.355	0:02.359	0:02.520	0:02.283	0:02.331
Turn 12	0:04.349	0:04.410	0:04.273	0:04.474	0:04.664	0:04.525	0:04.273	0:04.273
Turn 13	0:04.896	0:04.971	0:04.938	0:05.019	0:05.131	0:04.924	0:04.896	0:04.938
Str 0-1	0:05.898	0:05.913	0:05.890	0:05.860	0:05.946	0:05.779	0:05.779	0:05.890
Totals	**1:29.785**	1:30.124	1:30.028	1:29.984	1:32.719	1:30.110	1:28.885	1:29.642

Table 9.1 *An example of a report table for Section Times around Mid-Ohio.*



The sections are defined by the track map. The exact start and stop locations for every section is set by their distance from the beacon or lap marker. And because the beacon marker is usually across from pit row, both the in lap and out lap should be excluded from the table. Both laps cannot be trusted for reliable section times because the lap distances are different than complete laps. On the out lap the race car starts from pit lane. Therefore its distance to turn one is different than if it traveled down the front straight where the beacon transmitter is located. The in lap also cannot be included because the driver takes a different line through the last corner exiting the race track onto pit lane. Besides, the out lap should be a warm up lap while the in lap should be a cool down lap. Therefore always remove these laps from reports on Section Timing.

Note: An *in lap* and *out lap* could occur in the middle of a data set. If the car came into the pits and left without downloading then the subsequent download will contain two outings and two sets of in and out laps.

△ Warning: Brake lockup on both front wheel speeds will generate an error prone distance because the car is moving forward while recording zero speed. Such instances usually require the removal of the entire lap from Section Timing as the distance calculated for the rest of the lap is incorrect. Once the car crosses the lap beacon again, the lap distance calculation is reset and good to go.

Fastest Rolling Lap

The fastest rolling minimum lap is found by recursively subtracting sections of one lap and adding those sections of the next lap, all the way through every lap. In simple terms, if a person was to walk around the track and take lap times from the start of every section rather than only the start / finish line, then the fastest lap recorded will most often be different than the official timing. This is called the fastest rolling lap. Think of it as being able to move the start / finish line to any place around the track and take the fastest lap time. In ***Table 9.1***, the fastest rolling lap is marked by a vertical red line starting before Turn 9 of lap 3 and continues through lap 4 till it reaches the same point.

The fastest recorded lap time based on the beacon location was:

- **1:29.785** - fastest actual lap time found on lap 1

The fastest rolling lap was:

- **1:29.642** - fastest lap time with the start /finish line moved to Turn 9

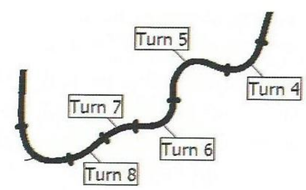
This can be a great emotional boost to help the driver feel better about their lap times. Now if only the driver would have done that all within one lap instead of two consecutive laps!

The fastest rolling lap is an actual lap completed by the driver. It is often confused with the fastest theoretical lap, which is not an actual continuous lap completed by the driver. Lets explain this in more detail....

Fastest Theoretical Lap

If all of the fastest sections (in blue) were added together to form one lap, this would be the fastest theoretical lap time labeled in the table as the Eclectic lap. In our Mid-Ohio example found in ***Table 9.1***, lap 1 was the fastest lap at 1:29.785 and the fastest theoretical lap time was 1:28.885, almost a second faster. While this number is great for bragging rights during bench racing with fellow drivers, it might not be possible. All too often, the track is divided into sections based on the official track map. In our Mid-Ohio example, 13 turns result in a total of 19 sections. The problem with the fastest theoretical lap time is that one section often influences another section.

Take for example Turns 4 through 6:



	Mid-Ohio						Eclectic
	Lap 1	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6	
Turn 4	0:02.074	0:02.117	0:02.051	0:02.052	0:02.228	0:02.095	0:02.051
Turn 5	0:06.129	0:05.982	0:06.139	0:06.070	0:06.786	0:06.090	0:05.982
Turn 6	0:05.087	0:05.120	0:05.119	0:05.173	0:05.363	0:05.175	0:05.087
Turn 7	0:02.916	0:02.886	0:03.003	0:02.985	0:02.941	0:02.878	0:02.878
Turn 8	0:03.678	0:03.645	0:03.622	0:03.567	0:03.863	0:03.753	0:03.567

Table 9.2 *Turns 4 through 6 influence each other in a major way. Turns 7 and 8 also effect each other.*

- On Lap 3, the driver generated the fastest section time on Turn 4, but as a result Turn 5 was 0.157 seconds slower. So Turn 5 suffered to obtain a faster time in Turn 4.
- On Lap 2, Turn 4 was sacrificed by 0.066 seconds which was used to setup for a faster time through Turn 5. Because Turn 5 being driven as fast as possible Turn 6 was also thrown away.
- On Lap 1, Turn 5 was sacrificed by 0.147 seconds in order to achieve the fastest section time for Turn 6.

The fastest section times for Turns 4, 5 & 6 were generated from only three laps. But it would not be possible to drive all three of those fastest sections times together on one lap because each corner influences the others. Therefore the Eclectic is not possible. Also take a look at Turns 7 & 8 for Laps 4 and 6.

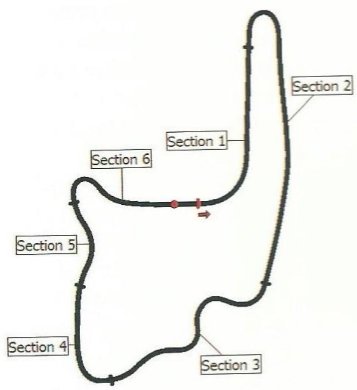
- On Lap 6, the fastest section time for Turn 7 occurred but Turn 8 was slower.
- On Lap 4, Turn 7 was slowed to create a faster section time in Turn 8.

△ *Warning:* When a track is broken down into too many sections, often the official track map sections, the Eclectic or fastest theoretical lap time is not possible.

Grouping Sections Together

There is a way to make the fastest theoretical lap time represent a lap time that could actually be driven. This can happen by grouping together those sections which influence each other. For a typical track there should be anywhere from 4 to 8 sections depending on the circuit layout. Any section that influences another needs to be grouped together. For example, the speed at the end of a straight is dependant on the speed exiting the prior corner. Therefore any straight needs to be grouped together with the corner that precedes it. The braking zone prior to that corner influences the corner. Therefore a natural separation to start sections would be right before each major braking zone.

At Mid-Ohio the following groupings would apply:



Section 1:
Turn 1 and the following straight.
Section 2:
Turn 2 and the following straight.
Section 3:
Turns 4 thru 8.
Section 4:
Turns 9 and the following straight.
Section 5:
Turns 10 & 11.
Section 6:
Turns 12 thru the following straight.

	Mid-Ohio						Eclectic	Rolling Minimum
	Lap 1	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6		
Section 1	0:13.593	0:13.627	0:13.504	0:13.446	0:13.511	0:13.396	0:13.396	0:13.446
Section 2	0:23.619	0:23.736	0:23.946	0:23.706	0:24.318	0:23.629	0:23.619	0:23.706
Section 3	0:20.356	0:20.228	0:20.404	0:20.318	0:21.693	0:20.471	0:20.228	0:20.318
Section 4	0:10.785	0:10.939	0:10.770	0:10.838	0:11.125	0:10.899	0:10.770	0:10.770
Section 5	0:06.477	0:06.484	0:06.484	0:06.514	0:06.517	0:06.700	0:06.477	0:06.484
Section 6	0:14.952	0:15.106	0:14.917	0:15.160	0:15.552	0:15.013	0:14.917	0:14.917
Totals	**1:29.785**	1:30.124	1:30.028	1:29.984	1:32.719	1:30.110	1:29.408	1:29.643

Table 9.3 *Revised section times based on corners grouped together.*

If you compare the fastest theoretical lap time of our grouped sections, **1:29.408** seems much more plausible for this driver than a time of **1:28.885**. The Eclectic time is now an acceptable goal for the driver. Notice the rolling minimum is the same in both cases, as would be expected because this lap truly did happen.

For those sessions when there is so much traffic that a single clear lap is not possible, the fastest theoretical lap, or Eclectic, can be used to estimate what lap times would be without traffic.

Consistency

With the fastest sections highlighted in blue, all of the other boxes can be colored to represent the consistency of a driver. If a section time is within 1% of the fastest time shown in the blue boxes, it will be colored in light green. If the section time is greater than 1% but less than 2% the box is colored in dark green. Any section time greater than 2% of the fastest will be shown in a white box. A consistent driver will have all green and no white boxes. An inconsistent driver will have lots of white boxes with few greens. In the example on the prior page of ***Table 9.3***, this driver had lots of green boxes. The only lap with lots of white was lap 5. Perhaps the driver was cooling down tires or stuck behind traffic?

Looking at more examples of Mid-Ohio, ***Table 9.4*** has most boxes in light green showing great consistency. That's not to say a professional driver won't ever have any white boxes. New tires often take a lap or two to come up to temperature and pressure. These out laps on cold tires will have some white boxes. Note the rolling minimum is all from one single lap. Great drivers are capable of putting it all together in one lap when it comes time to qualify!

	Mid-Ohio					Eclectic	Rolling Minimum
	Lap 1	Lap 2	Lap 3	Lap 4	Lap 5		
Section 1	0:13.384	0:13.413	0:13.260	0:13.347	0:13.278	0:13.260	0:13.260
Section 2	0:23.687	0:23.725	0:23.549	0:23.664	0:23.611	0:23.549	0:23.549
Section 3	0:19.885	0:19.998	0:19.958	0:19.942	0:19.910	0:19.885	0:19.958
Section 4	0:10.827	0:10.836	0:10.761	0:10.792	0:10.792	0:10.761	0:10.761
Section 5	0:06.492	0:06.511	0:06.450	0:06.499	0:06.548	0:06.450	0:06.450
Section 6	0:15.012	0:15.009	0:14.848	0:14.850	0:15.015	0:14.848	0:14.848
Totals	1:29.289	1:29.494	**1:28.830**	1:29.097	1:29.158	1:28.756	1:28.830

Table 9.4 *A true professional driver qualifying at Mid-Ohio. Notice the consistency in times and how the theoretical fastest lap is only 0.074 seconds faster!*

To determine what makes one section faster than another, simply overlay that section with another lap using a graph of speed and variance. In looking at ***Table 9.3***, lap 5 is considerably slower than most of the other laps. Perhaps a graph of speed might help to explain why?

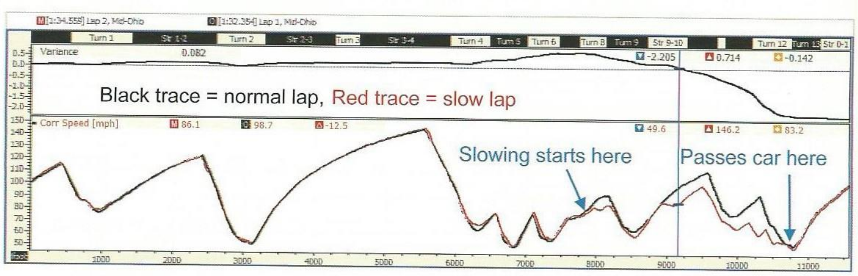


Figure 9.1 *Lap 2 shown in red is slowed considerably near the end of this lap. It appears to be caused by traffic, with the pass of the slower car happening in the last turn. Onboard video would confirm the traffic excuse by the driver. The lap could have been faster, given the red trace gained time through Turns 4, 5 & 6.*

Chapter 10 Video

Gone are the days of installing consumer grade 8mm video tapes. Digital video recorders are now smaller, lighter and more user friendly than ever before. Digital video recorders vary from a couple hundred dollars to many thousand. Motorsport quality recorders are far more expensive, but they are built to take the abuse in which a motorsport environment demands. Most importantly, get one that integrates and will synchronize to your logged data. *The synergy of syncing video with your car's data can provide epic rewards*!

When the video is synced to the data, many advantages exist that wouldn't otherwise be available if the video is played back on its own. The data analysis software can playback at slower speeds, do loop playback of one corner over and over again, and most importantly locate a specific point in the video by identifying it in the data. Multiple cameras can all be synchronized in playback. One camera can be used to study feet movement during braking and down shifts. One camera can be aimed at the driver's hands and steering wheel movements. And of course the most important view is out the front of a race car, which is what the driver sees.

Another major advantage with integrated video is the ability to replay two laps side by side, in distance mode. This is done by playing the first video at real time, and speeding up or slowing down the overlay video such that the frame of the overlay video corresponds in distance to that of the main lap video.

Not only is video helpful for driver analysis, it can provide many other key benefits for the engineering of the car. Video can be used to analyze sidewall deflection in a tire, visual airflow with string taped to the surfaces, and show flex in the chassis.

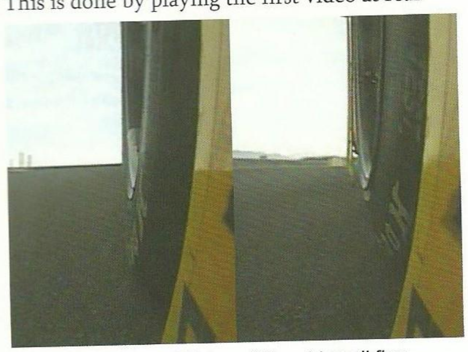


Figure 10.1 *Video of tire sidewall flex.*

Figure 10.2 *This digital video recorder can use up to four camera inputs at the same time and be synchronized with the logged data for playback.*

In this next example, both video and GPS are used to analyze driving lines around a left handed corner. In the bottom left corner are the driving lines plotted from GPS data. Video in the center of the screen shows the car on the left corresponding to the data colored red, while the car on the right is the data colored black.

Here at the entrance to Turn 6 where the cursor is located in ***Figure 10.3***, the car on the right (black trace) drives down into an early apex. Notice how the front left tire is next to the red and white curb. The video on the left (red trace) is a few feet off the curbing. The black trace carries more speed into the corner as seen in the speed trace of about 4 to 5 mph. The car on the left drives a bit slower into the corner, setting up for a different driving line. The advantage on corner entry is clearly with the black trace.

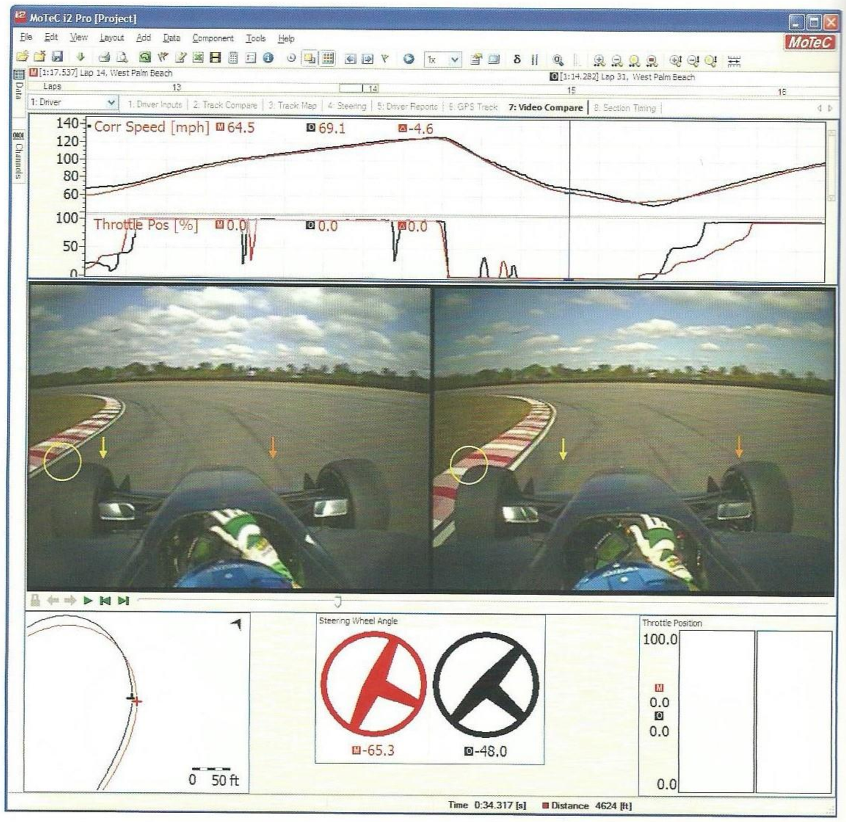


Figure 10.3 *An example of video and GPS synched with data.*

In ***Figure 10.4*** below, the cursor is located at the beginning of the exit phase of the corner. The car on the left (red trace) maintains a higher minimum speed through the corner. But the car on the right (black trace) was able to get onto the throttle sooner and has a higher speed traveling down the following straight. Notice the placement of the car in both pictures, with respect to the curbing on the left side and the skid marks on the pavement. With the video on the right two black marks appear in front of the FR tire. But these same marks in the video on the left appear many feet to the right of the car. This is verified and seen in the GPS lines of the bottom left corner. The two lines are dramatically different thanks in part to a very wide track width.

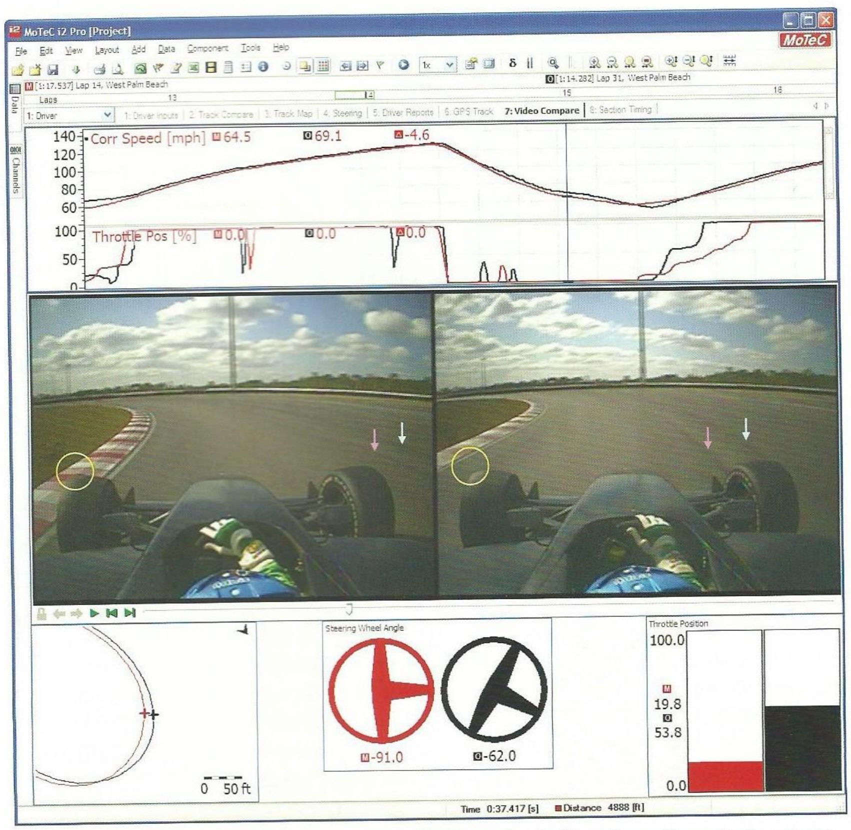


Figure 10.4 *Another example of video and GPS synched with data on the exit of a corner.*

Chapter 11 Putting it All Together

This book wasn't written to explain vehicle dynamics, or instruct you on how to adjust the race car. And it wasn't written to coach drivers. The goal was to help you make sense of the data you've collected on your race car. Now that you're armed with the knowledge of how to read all those squiggly lines of data, how do you actually apply all of it? Unfortunately there is no exact recipe to follow because every situation is different.

Those familiar with racing know, there are only two things that can be changed to go faster. One is the car. The other is the driver. Under each one is an endless maze of complexity that must be studied to extract the best. Getting one or the other right can produce a race win. And when one side is lacking, the other must compensate. But the harmony of both working together is what creates champions.

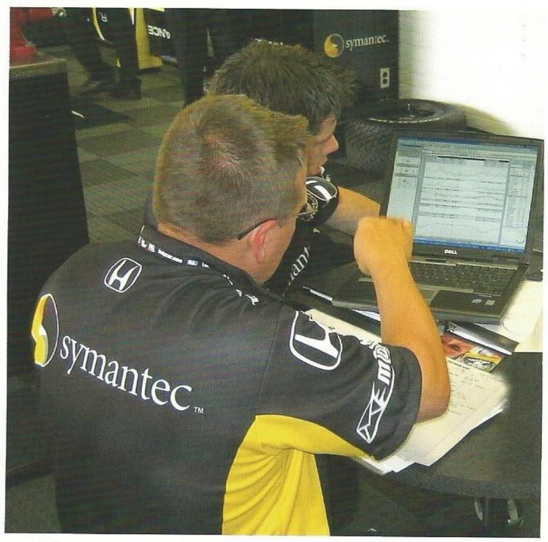


Figure 11.1 *Engineers Ray Leto and Leigh Pettipas looking over data and discussing the car's balance.*

For novice drivers, the gains to be found in the driver are bigger than that gained by making changes to the car. For professional drivers, the gains to be found in the car are typically bigger than those found in the driver. If there is any room for driver improvement, this should always be the first priority. Think of driver training and coaching as an investment with a return that lasts a lifetime.

Having all the data in the world will be of little to no use if the driver is mentally overloaded. A novice driver can be overwhelmed by all the information presented to him or her while driving a race car. The torque in the steering wheel, the forces through the seat, the visual sight, the history of what the car was doing in the moment before the present time and the anticipation of what might happen next. As great as data can be, if the driver can't process all of the information fast enough, then that is the limiting factor. No amount of data will help. Try to get the driver training in a race car which is faster reacting than what they would normally be driving. Such a car will force the driver to speed up their thought process.

11.1 Strategy for Improvement

Analyzing data can become a full day's job. For professional teams, additional staff are hired to tackle this task. But for club level racers, the driver himself often handles the analysis. Having the driver be the engineer can add extra time requirements and therefore stress over what should be a fun and relaxing weekend. Spend some time between races, away from the track looking at data. When looking at data while at the track, do so where there are no interruptions.

While this book was written for the engineer, and makes reference to the driver, it is equally acceptable for the driver to be their own engineer in which any references to "driver" would be a reference to "yourself".

As taught in many racing schools, you first must get the racing line down consistently before going fast. This includes braking, turn in, cornering, exit throttle, etc. Identify repeated mistakes as the top priority. Focus on being consistent. Changes to the driving style or the driving line could be a fluke, unless they are demonstrated lap after lap. Remember to compare all of the laps and not only the fastest one or two.

Start with a speed trace. Identify areas around the track where speed is lacking by comparing to a faster driver. If no faster driver data is available, use variance and section times to help identify the fastest sections which could be driven more consistently faster. These are the areas to concentrate on first.

Never send a driver out with multiple areas to improve on. Focus his or her attention on one or two items at most. Set achievable, measurable goals for each upcoming session. Review these directly after each session. Be more specific than "go faster". Where will the driver go faster? How will the driver do it? Will it change the braking points, turn in point, driving line, etc? Discuss each target in detail with the driver. Once that goal is mastered, and other areas didn't suffer, then move on to additional ones.

To build a fast driving line, work on exit speed first with the aim to maximize speed down the straight. Then increase entry speed slowly until the minimum cornering speed is maximized. Finally start braking later.

It's important to know where the car is already at its limit, and where it isn't. When reviewing data, decide which areas for improvement are beyond the driver's current talent level. Be safe.

The importance of GPS data for verifying and confirming changes in the driving line cannot be understated. Neither can the use of video. Use it with data.

Take good notes during and after the session on all potential variables. Track condition, weather, car setup, tire pressures, condition of the tires, and even traffic. Remember which laps had traffic making them slower, and which laps had drafting making them faster. The notes are even more important when returning to the same track again. Any of these variables could create differences in the data making analysis more difficult. Also take notes when analyzing the data. Start with a pad of paper and jot down ideas as they come to you. Store these notes with your car setup sheets or in the data file itself.

11.2 Summary of Channels

A quick review of the analysis for the 6 basic channels:

Speed – The holy grail of data.

- overlay laps to spot areas for improvement
- determine braking points, application and effectiveness of braking
- evaluate different driving lines around corners
- find minimum cornering speeds and maximum straight speeds
- analyze straight line speed for aerodynamic or engine power changes

With individual wheel speed sensors, additional items include:

- a lack of partial lockups indicates a driver isn't braking hard enough
- to many lockups identify too much braking or a possible bias problem
- wheel spin identifies traction or differential problems

Engine RPM –

- determine what engine speeds the driver is shifting at
- check for over revs
- analyze down shifts for consistency
- comparing aerodynamic drag or engine power more accurately than speed
- find the operating range of engine to help the engine tuner

Gear – Not used for much other than making sure the driver is in the optimal gear for accelerating. Useful for a quick check when comparing drivers.

Throttle – Equates to engine power.

- look for throttle lifts
- check for ideal throttle application existing corners
- verify good down shift throttle blips

G Force Long –

- determine braking effort
- find brake points more accurately than speed
- analyze release of brakes, important for trail braking

G Force Lat –

- measure the driver's ability to utilize tire grip when cornering
- analyze the ability of a driver to trail brake along the traction circle
- find turn in points when steering angle isn't logged
- evaluate changes to the car based on cornering ability

Steering Angle – One of the main driver inputs.

- locating the turn in point for a corner
- estimate the turning radius, and hence driving line from the amount of steering angle
- locate understeer and oversteer balance problems

Appendix A – Recommended Logging Rates

Basic Channels	Min	Normal	Fast	Max	
- Speed	10	20	50	100	depends on # of teeth per rev
- RPM	10	20	50	100	
- Gear	5	10	10	20	
- Throttle	10	20	50	100	
- Steering	10	20	50	50	
- G-force*	10	10	20	20	

*with anti-alias filter turned on in the logger. If your logger does not do anti-aliasing, then log 10 times faster and apply appropriate filter.

Engine Channels	Min	Normal	Fast	Max
- engine temperature	1	1	2	5
- oil temperature	1	1	2	5
- oil pressure	5	10	20	50
- fuel pressure	10	20	50	50
- fuel temp	2	5	10	10
- air temp	1	2	5	10
- manifold pressure	10	20	50	100
- barometric pressure	1	1	2	2
- crankcase pressure	5	10	20	20
- lambda	5	10	20	50
- ignition advance	5	10	50	100
- exhaust gas temp	5	10	20	50

Chassis Channels	Min	Normal	Fast	Max	
- brake pressure	10	20	50	100	
- brake temp	5	10	20	50	
- damper position	10	20	50	50	chassis movements(roll, pitch)
- damper position	100	200	500	500	for shock velocity histograms
- ride height	20	50	100	100	
- suspension load	20	50	100	200	faster w/o anti-aliasing filter
- tire temp	5	10	20	50	
- pitot tube pressure	10	20	50	100	
- yaw rate sensors	10	20	50	100	
- bearing temperature	2	5	10	10	
- anti-roll bar setting	1	1	1	1	

System Channels	Min	Normal	Fast	Max	
- gearbox temperature	1	1	2	5	
- gearbox pressure	5	10	20	50	
- coolant pressure	5	10	20	50	
- battery voltage	5	10	20	50	
- gear shift force	100	200	200	500	for gear change power cut
- gear pos voltage	100	200	200	500	for gear change power cut
- gear pos voltage	10	20	50	50	no gear change power cut

Appendix B - Glossary of Terms

accelerometer – device used for measuring acceleration otherwise known as G forces acting on a car. Usually a piezo electric device, where a small block sits on a moveable substrate. As G-forces act on this block, it moves creating a signal proportional to how far it moved. See "G-force".

accuracy – the closeness of the measured value to its true actual value.

Analog-to-Digital converter – the device responsible for converting an analog signal into a discrete digital form. Ex: sensors provide a variable voltage signal output, which the A/D converts into a digital form of 0's and 1's.

anti-alias filter – averaging multiple samples to get a single sample point that is more indicative of the time range it represents.

apex – the location where the race car touches the inside edge of a corner.

balanced throttle – maintaining enough throttle application to keep a vehicle at a constant speed, neither accelerating or slowing down.

beacon – device used for lap marking as the car runs around the track. Typically consists of a transmitter located trackside and a receiver mounted in the car.

calibrate – to specify the output of a sensor based on the voltage it outputs into a physical parameter like speed, pressure, temperature, etc.

channel – a single parameter such as rpm, wheel speed, throttle,… etc. typically measured from a one sensor, or some calculation thereof.

corner entry speed – speed at the point of turn-in.

corner minimum speed – the lowest speed reached during the corner .

corner exit speed – speed when full throttle is reached exiting out of a corner.

DAS – Data Acquisition System, the collection of logger, sensors and wiring which complete the entire system.

DAG – Data Acquisition Guru, person who works with data acquisition.

DGPS – Differential GPS uses geostationary satellites for correctional information to increase accuracy.

data logging – the act of recording information, measurements, etc.

downloading – the act of transferring data out of the car and into the computer.

differentiation – a mathematical evaluation, reporting on how quickly the values are changing either up or down. For example, how quickly a car accelerates is the differentiation of speed, otherwise known as acceleration.

integration – a mathematical evaluation, reporting on the opposite of differentiation. It sums up the total amount over time of a channel.

EGT – Exhaust Gas Temperature.

filter – a mathematical evaluation which averages the recorded values over time.

frequency – The rate at which an event happens, such as "10 times per second".

G Force – a unit of measure based off the Earth's gravitational pull ($9.81 m/s^2$). Force = Mass * Acceleration, where G force is the acceleration component not force.

G Force Lat – force in the lateral direction (left / right).

G Force Long – force in the longitudinal direction (fore / aft).

G Force Vert – force in the vertical direction (up / down).

Hertz – unit of measure, 10 Hz = 10 times a second.

histogram – A chart which adds up the time or percent of time an item is within a certain range called a bin.

lambda – this number represents a fuel independent measurement of the air to fuel mixture ratio, normalized to a value of 1.0 for stochiometric burn.

linear potentiometer – sensor which measures linear movement (shocks).

lateral G – amount of acceleration due to cornering. See "G Force Lat".

logging – the act of recording information.

logging rate – the rate a channel is recorded, reported as Hertz. See "Hertz".

longitudinal G – amount of acceleration during accelerating or braking. See "G Force Long".

LVDT – linear variable differential transducer, a sensor used for measuring linear movement with high accuracy.

noise – mechanical or electrical interference that effects the desired reading of a sensor. For example; accelerometers are typically subjected to chassis vibration which is not of interest.

overlay – to display more than 1 lap on a graph, therefore having multiple traces from 2 or more laps.

oversteer – when a vehicle is turning greater than the driver has turned the steering wheel. Opposite of "understeer".

pitch – the angular rotation of the car about the longitudinal plane. When braking this will typically cause the front of the car to go down, and when accelerating the rear of the car goes down.

pitot tube – a small hollow tube placed to measure the wind speed over a vehicle.

precision – the closeness of repeatability when multiple measurements are taken.

resolution – the discrete steps a signal will experience when changing value.

roll – the angular rotation of the car about the lateral plane. When cornering in a right hand turn, the car rolls to the left.

rotary potentiometer – sensor which measures angular rotation (steering).

RVDT – rotary variable differential transducer, a sensor used for measuring rotating movement with high accuracy.

sample – a collection of data.

sampling (rate) – misused term, see "logging rate".

segment time – time to complete a track section or segment.

sensor – device which generates a signal, typically a variable voltage, to represent a physical measurement of some parameter such as speed, temp, pressure, etc.

sensor – a device which measures.

signal – the voltage or other value being sent from the sensor to the logger.

signal conditioning – manipulation of an incoming analog data to improve results during the conversion into a digital format for logging.

slip angle – angle of the car with respect to the direction of travel. Can also refer to the tire angle with respect to the direction of travel.

standard deviation – a statistical amount of variation, noise or error, the higher this number the more variation exists (less precision).

steered angle – the angle of the steered tires with respect to the chassis.

steering wheel angle – the angle of the steering wheel.
strain gauge – small devices that measures strain or force. Often requires an amplifier since the voltage output is very small.
telemetry – the transmission of information from a distance.
thermocouple – small device which measures temperature. Requires an amplifier since the voltage output is very small.
throttle angle – represents the angle of the throttle blade. Usually represented as a ratio from 0% to 100% rather than an angle.
throttle blipping – quick stabs at the throttle pedal done during down shifts in order to match the engine RPM with the requirement of the next gear down.
throttle position – represents a ratio of throttle from 0% to 100%.
tire slip angle – tire angle with respect to the direction of travel.
trail braking – done when entering a corner, trail braking is the method used to add steering angle while releasing the brake pedal at the same time in order to maximize grip by driving on the outer edge of the traction circle.
understeer – when the vehicle does not turn at the amount of which the steering is turned. Opposite of "oversteer".
yaw – the angle of the car with respect to its traveling direction.
yaw rate – the derivative of yaw. The rate at which the yaw of a car is changing.

Appendix C - References and Recommended Reading

Ross Bently, *Speed Secrets*, MBI Publishing Company, Osceola, WI, ISBN 0-7603-0518

Ross Bently, *Speed Secrets 2*, Motorbooks International, St. Paul, MN, ISBN 0-7603-1510-8

Buddy Fey, *Data Power: Using Racecar Data Acquisition*, Towery Pub, Memphis, ISBN 1-88109-601-7

Denis Jenkinson, *The Racing Driver*, Robert Bently, Inc, Cambridge, MA, ISBN 0-8376-0201-7

Carl Lopez, *Going Faster!*, Robert Bently Publishers, Cambridge, MA, ISBN 0-8376-0227-0

Claude Rouelle, seminar on *Vehicle Dynamics, Race Car Engineering with data acquisition*, Optimum G, Denver, CO, February 2002

Carroll Smith, *Race to Win*, Carroll Smith Consulting, Inc, CA, ISBN 0-9651600-0-9

Index

Race Car Data Acquisition, Basic Analysis

Data points are just words, but when connected with a squiggly line they tell a story...

Race cars existed before computers. But in today's professional racing, the car never leaves pit lane until the computer system is calibrated and ready to record. It records how the car reacts to driver inputs (hands and feet) and track inputs (turns and bumps). This book covers how to analyze the basic channels of data which are: *Speed, RPM, Throttle, G-Forces and Steering.* Anyone with a little racing knowledge will be able to read this book, analyze data and go faster.

What can you do with data?

- compare driving lines
- identify turn in points
- compare laps with video
- time variance between laps
- find understeer & oversteer
- evaluate aero changes
- locate throttle lifts
- locate ideal throttle traces
- analyze braking zones
- perfect trail braking
- set brake bias
- optimize gear shift points
- driver coaching
- GO FASTER!

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