THE

PERFECT CORNER

A Driver's *STEP-BY-STEP GUIDE* to Finding Their *OWN OPTIMAL LINE* Through the *PHYSICS OF RACING*

THE SCIENCE OF SPEED SERIES

PARADIGM · SHIFT
DRIVER DEVELOPMENT

THE PERFECT CORNER

THE **PERFECT** CORNER

A Driver's
STEP-BY-STEP GUIDE
to Finding Their
OWN OPTIMAL LINE
Through the
PHYSICS OF RACING

The Science of Speed Series

created by PARADIGM SHIFT DRIVER DEVELOPMENT
written by ADAM BROUILLARD

PARADIGM · SHIFT DRIVER DEVELOPMENT

www.paradigmshiftracing.com

ISBN-10: 0-9973824-2-2
ISBN-13: 978-0-9973824-2-6

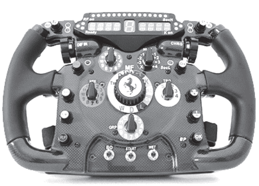
Published by Paradigm Shift Motorsport Books
The Perfect Corner and The Science of Speed Series are trademarks of Paradigm Shift Driver Development.

www.paradigmshiftracing.com

For information about custom editions, special sales, premium and corporate purchases please contact:

Paradigm Shift Driver Development
development@paradigmshiftracing.com
470.240.1582.

CONTENTS



THE PHYSICS OF RACING 14

CORNER EXIT AND THE APEX 26

CORNER EXIT POWER APPLICATION 32

APEX ANGLE 38

CORNER EXIT CHEAT SHEET 43

CORNER ENTRY 45

EULER SPIRAL VARIABLES 50

CORNER ENTRY TROUBLESHOOTING 57

ALTERNATE CORNER ENTRIES COMPARED 64

THE ACCELERATION ARC 71

ADVANCED CORNER ENTRIES 77

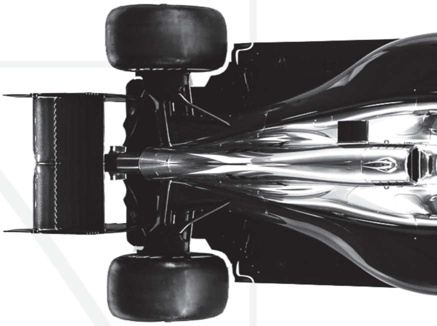
THE DRIVER’S EYE VIEW 83

BONUS SECTION: ADVANCED RACING PHYSICS 90

GLOSSARY OF MOTORSPORT TERMS 97

THE PERFECT CORNER

Is there such a thing? The perfect corner, the perfect lap? Many drivers don't realize, but for a given car, setup, and conditions there is in fact a singular optimum way to navigate a racetrack in the minimum time possible. A set of fundamental physics based rules exist that can guide you in your never-ending pursuit of speed.

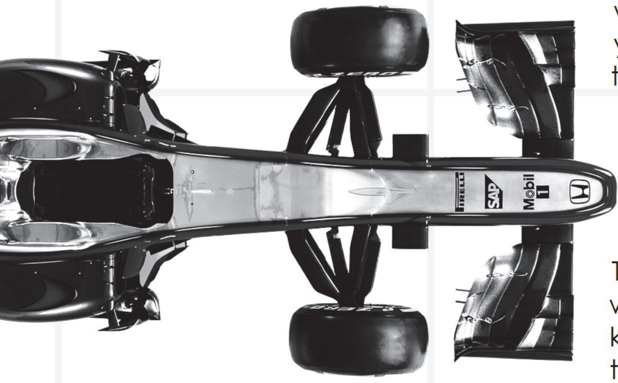


This quest to come ever closer to perfection is what drives many of us. This pursuit is one of the beauties of racing as the stopwatch always provides a measurable goal that you can always improve on. There is always that last second. That last 10th. That last 100th.

While a driver will never be able to achieve a truly perfect lap in reality, there is one place an actual perfect lap can exist. It can exist in the mind and give a driver a goal they can always strive to reach. That is what this book will introduce and explain. A set of rules that take a physics based approach to finding an optimal solution on track and distilling it into an intuitive way of driving that racers at any level can begin to apply.

We will take you through a fun thought experiment that will introduce the physics of racing and then learn to apply it as we optimize some real world corners. All with precise instructions and answers, but broken down so it's easy to understand. We will provide an exact method to find the optimum strategy all from the driver's eye point of view. No advanced vehicle dynamics knowledge is needed.

Understand though, that while the strategies we will learn to break down and analyze a track might be new, the actual driving techniques are not. We don't offer a secret new weapon that will have you smashing track records by next weekend. Although they may not all have understood exactly why they drove the way they did, many of the top drivers in the world have been driving by the principles that we teach for decades. You can find old videos of champion drivers like Senna, Schumacher, and others driving laps that reflect these methods. We actually recommend reviewing videos of world-class drivers as you work through this book. Try to identify how what you are learning is reflected in the videos of their top performances.



So we don't offer an instant path to the top podium step. A good bit of car control training will be required for that. But one thing you can develop quickly is knowledge. The knowledge to never be confused about what you should be doing on track. The knowledge to know exactly where you are losing time, and what those champion drivers are doing that makes them faster. You will no longer have to rely on trial and error. You will no longer have to try to mimic the laps of faster drivers. Instead, you will be able to watch their laps and identify where **they** are losing time. You will have a solid goal to focus on as you reach ever closer toward perfection. Learning this new method will require a commitment from you however, because it will probably be a true paradigm shift in the way you will look at a racetrack from now on. For many novice drivers with little previous knowledge this should be easier, but for veterans, you may have to set aside previously held assumptions.

PAR · A · DIGM SHIFT

NOUN

A FUNDAMENTAL CHANGE IN APPROACH OR UNDERLYING ASSUMPTIONS.

LINE THEORY

When a novice first gets into motorsport they will often be taught a basic racing line and then instructed to steadily increase their speed. This is a good approach as it is generally a safe way to learn and will eventually produce some respectable lap times.

Line Theory is the term we use for the set of rules you will use to optimize your path.

At a certain point however, this student will usually hit a wall. They just can't go any faster and they can't figure out why. Many will then turn to data and video and look at laps of the faster drivers to try to figure out what the differences are. They will try to emulate what the faster drivers are doing and through trial and error and lots of work their lap times will slowly start to creep lower again. After years and years of driving different tracks and cars, they will build up a mental database of what to do at each corner and in each situation.

But there are a lucky few who seem to be able to almost bypass this process entirely. They just have a natural instinct for what it takes to go around a track quickly. Whether they realize it or not, they are following the basic principles of physics that produce lower lap times. Just like the gifted child that knows instinctively how to move their body to put the maximum power behind a ball being kicked or thrown, these drivers seem to have an innate grasp of the fundamentals that create a champion driver.

They can quickly move beyond a basic learned racing line and actually create an ideal one as they drive. While learning a basic racing line can take you quite a way, if you wish to reach your ultimate potential you'll need to go beyond the basics and learn the rules that created that line in the first place.

What makes a certain path the fastest way around a track? Why do we want to use the whole track? Why do we sometimes not? What is so special about slow-in, fast-out? In short, what are those champion drivers doing that makes them so darn fast, lap after lap?

While this ability only comes naturally to a select few, luckily it can be learned by just about anyone and it doesn't require a PhD in physics either. Everything the driver needs to know is actually fairly simple and can be broken down into a set of fundamental rules. We call these fundamental rules Line Theory.

We say these drivers are creating a line as they drive because there is actually no such thing as a correct line. Only the correct line at this exact moment and it will change based on where exactly your car is right now and how it responds at the limit. There is no reason to worry about trying to learn an ideal line until you are driving at your limit, because what happens at the limit is actually creating your line.

We will teach you instead to focus on the limits of the track and then use Line Theory rules to constantly optimize your driver inputs based on these track limits. Because of this, you will need to start thinking of the line more as a result than a path to follow. Every small variance and mistake will change how you optimize the rest of the corner at every instant. We'll see how all you are really doing is constantly correcting mistakes during a corner. Ideally, very small mistakes.

Therefore, while Line Theory rules will never change, your ability to control the car will cause the resulting line to change. As your car control skills improve and evolve, so will your optimal line. Even if you have excellent car control skills though, there will always be at least some variations that change how you will optimize a corner each time. The resulting line and the driver inputs used will never be exactly the same even if they only change by the smallest of margins.

THE LIMITS OF CONTROL

In this last section, we mentioned that your optimal resulting line would change as your car control abilities change. Because of this, it's important to understand that Line Theory and car control need to be considered completely separate.

No matter what your skill level, you can still apply the fundamentals of Line Theory to improve your lap times.

The primary reason is that the ideal path you take will always be limited by your ability to control the vehicle. Although the rules will be the same, a novice driver will have a different resulting optimal line than an advanced driver. A quick example is that a more advanced driver will be able to control a car closer to the limit and would be able to turn more and achieve a higher speed by the point they put the power down for corner exit. This will require a different optimal apex than a novice driver.

There are a lot of Line Theory fundamentals packed into that example we haven't explained yet, but the take home point is that no matter what your skill level, you can still apply the rules of Line Theory to improve your lap times.

It's also important to understand that unless specified otherwise, we are always discussing the situation as if the driver is controlling the vehicle at the limit as best they can. One rule of Line Theory is that under normal circumstances, for ultimate lap time performance, there is never a time that you are not trying to use the vehicle's potential to its maximum. As a novice advances in their car control skills, that potential will change and thus their resulting line will change. How they apply Line Theory fundamentals will always however, stay the same.

It's also vital that you don't make the mistake of confusing failures in car control for failures in Line Theory. The differences we are talking about are sometimes only fractions of a second and most of the time a non-optimal technique done perfectly is going to be faster than an optimal technique done poorly. Drivers with superior car control abilities can make all sorts of non-optimal approaches work if they are only going up against drivers of lesser skill.

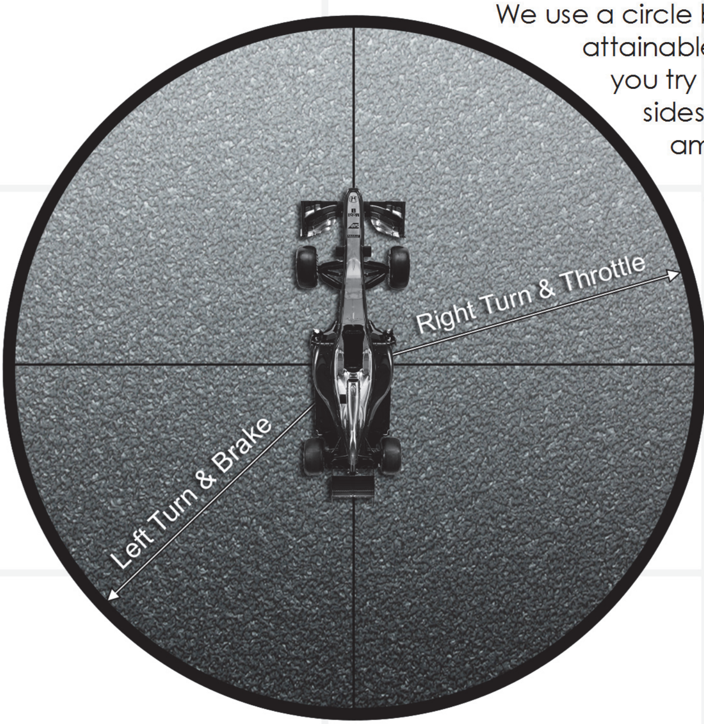
What's most important is that you understand **why** a technique is faster even if you haven't developed the car control abilities to do it properly yet. Line Theory is not a list of techniques to try out and see if they work for you and to discard if you are not immediately faster. Doing so shows a lack of understanding of what Line Theory represents. Line Theory is just the term we use for the application of the basic principles of physics on a racetrack. These principles are immutable until the physics of our universe decide to change.

Therefore, the most powerful aspect of Line Theory is not that it's just a list of rules that tells you the fastest way around a track, but once you have a complete understanding, you will **know** the fastest way. Wouldn't it be great if you could never have to worry about trying other lines, techniques, etc… because you know what you are doing is correct? It's a very powerful feeling to remove all doubt from your driving and know exactly why you were slow or why you were fast. Learning Line Theory will remove that doubt forever, and from then on, the only thing holding you back will be how far you can push the limits of your control.

VEHICLE DYNAMICS SIMPLIFIED

While there is certainly a lot of vehicle dynamics theory going on behind the scenes in this book, from the driver's perspective there is really very little you need to know once you are in the car. The only thing you really need to understand at this point to work through this book is that cars have an overall traction circle.

For those who are unfamiliar, a traction circle represents the concept that a car generates grip (or force) in all directions fairly equally. While each tire also has a traction circle and is generating a force, if you combine all those tire forces, you have an overall force acting on the car's center of gravity.

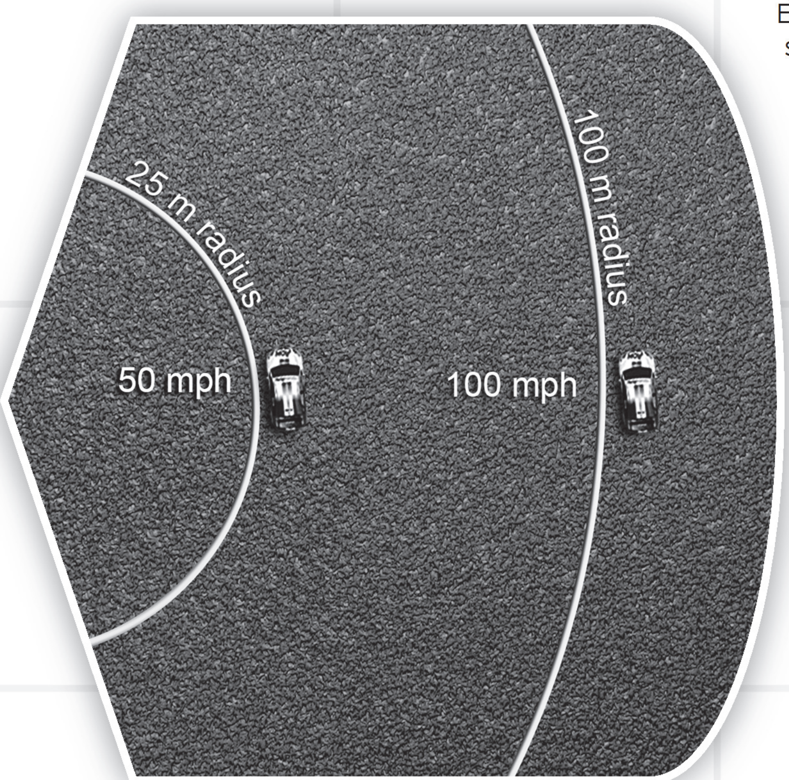


We use a circle because the maximum force attainable is fairly even in all directions. If you try to push a parked car from various sides, it will take roughly the same amount of force to get it sliding.

This same concept applies at speed and although there is a vast multitude of variables affecting the exact grip available at any instant, really all you need to know right now is the basic idea that it's similar in many different directions.

For example, a given car might either brake with 1 g of force or turn with 1 g of force or a combination of braking and turning that generates 1 g of force in a diagonal direction. Very few cars will be able to actually accelerate with the same force that they can brake or turn, but we'll get to that later.

Also realize that the traction circle is not just a pretty representation. You could actually imagine a jet thruster coming from the center of gravity pushing the car in the direction of the arrow. The tire forces will combine to create a net force on the car and this force will modify the car's path.



Expanding this concept, you should also understand that for any given radius a car travels on, it could only achieve a certain maximum speed. This basically means that if you drive a bigger circle, you can drive faster before the car is no longer able to maintain its arc. This should be fairly intuitive, but a quick example is that if a given car can drive at the limit around a 100 m radius circle at 100 mph, on a 25 m radius circle it would only be able to drive 50 mph before sliding wide.

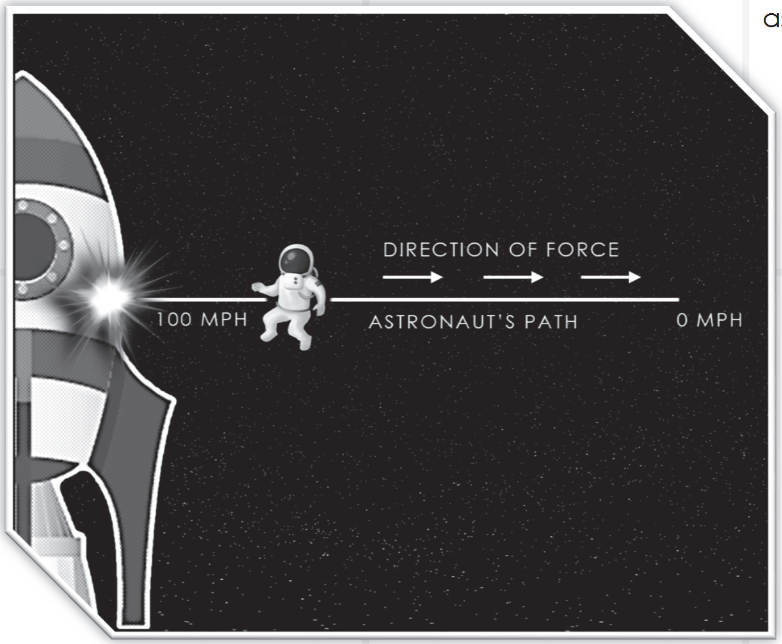
Grip vs speed is an exponential relationship and this example ignores aero effects, but that is not important right now. Just that you understand the general concept that a bigger circle allows a faster speed at the limit.

The forces discussed in this book are ultimately generated at the tire/track interaction.

This is pretty easy to understand when you have big changes in radius and speed, but realize this also holds true for small changes. Racecars will almost never be on a constant radius arc. They will normally either be increasing or decreasing their radius. As this radius changes, the attainable speed will also change. Even if the radius only changes by 1 cm, the attainable speed will also change. This is true with all cars including those with high downforce. A smaller radius will always require a lower speed and vice-versa. There is no free speed or grip, and you can't cheat the laws of physics.

ASTRONAUT RACING

Before we get into learning about how to drive the perfect corner on a racetrack, we find it useful to take a step back and look at the basic physics involved from an intuitive standpoint. A car, it turns out, is actually quite complicated, as you have to worry about silly things like steering, throttle, brakes, tires, and so on. Let's take all of that out of the equation and take a fun little detour… in space!



Imagine we have an unfortunate astronaut working on his ship when an explosion damages his suit and launches him into space at 100 mph directly away from the ship. Because his suit was damaged he needs to get back to the ship as **quickly as possible**, but his only source of propulsion is the fire extinguisher that he brought with him on his spacewalk for some reason. The fire extinguisher will let him generate maximum thrust in any direction virtually instantly. He just has to point it and pull the trigger.

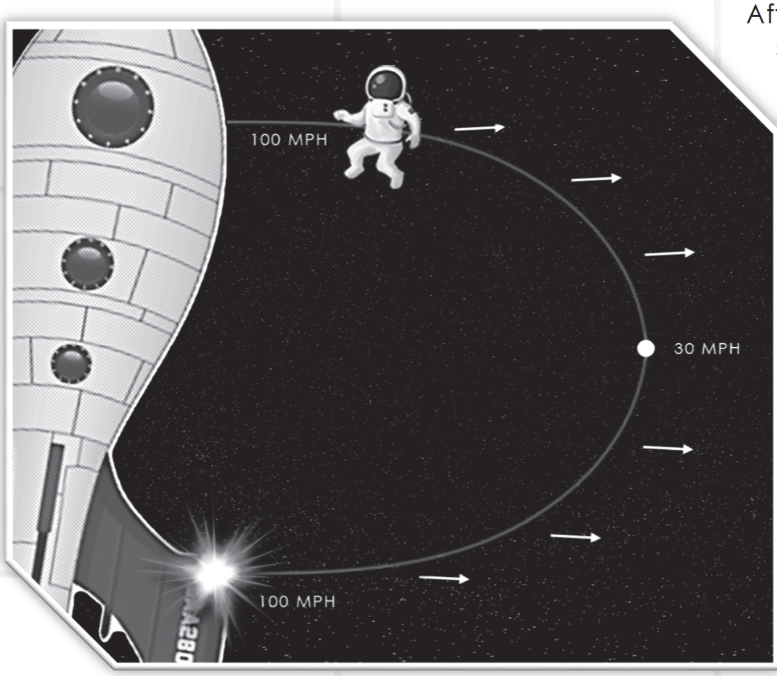
Our astronaut quickly surmises that to get back to the hatch as quickly as possible he will simply point the extinguisher away from the ship and blast away to bring him back to the ship in the minimum possible time. This will cause his 100 mph initial velocity to slow to zero and then he will begin to gain speed on the way back to the hatch. Let's ignore the hazardous side effect right now that he would enter the ship at 100 mph.

This simple thought experiment tells us two very important things right off the bat. The first is that to minimize his time to get back he wants to use the absolute maximum thrust he possibly can directly away from the ship for the entire flight. Our illustrations for this section will use arrows to depict the direction he is pointing his extinguisher. You'll see why this is important as we continue.

Secondly, if we plotted his speed vs time on a graph it will be a V shape with his speed starting at 100, then dropping to 0 and going back up to 100. The more force he can generate, the more angled the V shape and the lower his time in space. His minimum speed is also at the furthest point from the ship. Before moving on, make sure you understand the astronaut's actions because, believe it or not, what he just did is the very core of Line Theory.

INTRODUCING TURNS

Now let's start changing the scenario so we can see how this simple concept can be expanded. On his next mission, the very unlucky astronaut is working on the tail of his new ship at the other end from the entry hatch. There is an explosion yet again and he must get back to safety as quickly as possible. To reach his goal he's going to have to stop his outward motion and reverse it as well as move to the side in the direction of the hatch. We are going to assume he needs to enter the hatch straight on or he crashes into the side and explodes. This assumption will help to simplify this thought experiment.



After being launched into space, the astronaut, using his advanced physics knowledge, quickly points the extinguisher away from the ship but partially angled downward in the illustration to decelerate his movement away from the ship, but also start moving him laterally toward his goal. His speed will slow and once he's reached the farthest point away from the ship, he starts to accelerate back toward it.

At his farthest point, he needs to change the angle of the extinguisher to the other side so his path will slowly straighten and he'll arrive at the airlock dead on. The astronaut's actions cause his path through space to be in the shape of a parabola. Well-informed readers might recognize this as the basic shape of a racing line through a 180-degree corner. He decelerates to a minimum speed at the farthest point from the ship (the apex in racing terms) and then accelerates back toward it.

If he aimed his extinguisher perfectly in the proper direction, he just optimized his path to the hatch and it's impossible for him to get there any faster than this. The illustration shows his minimum speed as 30 mph, but the actual speed doesn't matter right now. What matters is that you understand that it's the minimum speed he will achieve. If you placed a floating cone out at the point he reaches his minimum speed, he would have also optimized his path around this obstacle as if it were a corner on a track.

It's not so much the shape of the path, but the direction of force that is important right now. The shape of the path is simply the result of that force. His extinguisher is always basically going to be blasting in the same direction opposite the ship. He does need to angle the extinguisher sideways to start and stop the sideways movement, but this is a relatively shallow angle and the majority of the force he feels is going to be his deceleration and then acceleration toward his ship. If you plotted his path using a speed vs time graph you would again see a V shape. The bottom of the V would be his minimum speed of 30 mph.

If you are having a hard time grasping why this one singular direction of force is so important to minimize the astronaut's travel time, try to imagine what would happen if he pointed his extinguisher in any other direction or didn't use maximum thrust. What would that do to his travel path and time in space? Some people are better at visualizing this than others, but it's very important to have an intuitive understanding of what we are explaining here so it's definitely worth the time to do your own thought experiments if necessary.

Before moving on we also wanted to point out that while the astronaut must angle his extinguisher to create the sideways movement, a car will also always have a similar sideways force generated while turning. Not to get ahead of ourselves here, but since a car can basically only generate force with its engine while going forward, it needs to do some rotating to be able to do that at corner exit. This needed rotation will require at least some sideways force.

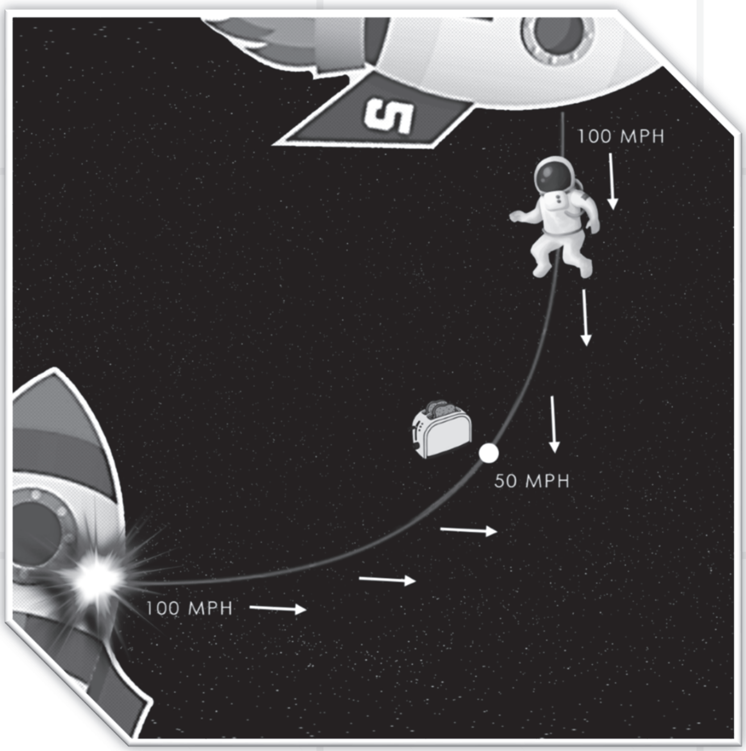
We don't want to overcomplicate this example, but did want to point out what that sideways angle of the astronaut's extinguisher related to in car terms. It's actually a driver's goal to minimize this sideways force by only using the bare minimum needed to move the car over to the apex. Any extra speed carried past the apex than is necessary just has to be reversed during corner exit. In a car, this will cause a driver to be unable to use as much throttle as would be optimal and this hurts their exit.

Minimizing these sideways forces leaves as much force as possible to be used in the primary direction. Throughout this book when we speak about the "ideal direction" we are referring to the direction that you are currently trying to accelerate in as quickly as possible by generating the maximum force attainable. Understand though, that there will always be some sideways force needed as well.

CHANGES IN FORCE DIRECTION

So now we understand that optimizing the direction of force is the key to the astronaut's salvation. So far these forces have basically always been going in the same direction, but let's now look at what happens when we change things up a bit to look more like a 90 degree turn on a racetrack and see how this affects our forces needed.

On his third mission, our astronaut starts to suspect that maybe he should seek a different career as he is blasted into space yet again. This time however, his ship is damaged beyond repair and he must make it to the sister ship. Unfortunately, there is also a piece of space debris in the way that he must first navigate around.



The astronaut again using his great understanding of physics looks at the obstruction and quickly calculates that he needs to immediately blast his extinguisher at a slight outward angle to slow him down from 100 mph and reach the corner of the obstruction at the proper speed. For this example, we made that speed 50 mph, but again, the actual speed is not important right now, just that you realize it's the slowest speed he attains on his trip. Also note that because the starting speed is the same as in the previous example, the needed direction of the extinguisher and the resulting shape of the path up to this apex is exactly the same as the beginning part of the previous path. You could overlay them and they would match up exactly. We will look at the reasons for this more in-depth in the corner entry section.

The better a driver can generate and direct these forces with their vehicle the lower their lap times will be.

Immediately as he passes the obstruction he turns his extinguisher to start moving him toward his goal in the minimum overall time possible. To keep this example simple the explosion launched the astronaut at the exact speed he would need to optimize this corner, but later we'll see how this optimal starting speed is determined. An analogous situation in a car for the explosion would be the point a driver decides to start turning their car during straight-line braking.

Again, we can see the shape of the astronaut's path, but also more importantly it shows the direction of force he is generating with the extinguisher. The key difference from the previous example is that once past the obstacle, the optimum direction of force changes. To travel in the minimum time possible around an obstacle, or in racing terms an apex, you want to generate as much force as possible pushing you backwards as you decelerate and turn toward the obstacle (apex) and then after you pass the obstacle you want to generate as much force as possible pushing you toward your final goal.

The direction of force needing to be generated simply follows the angle of the corner. If you moved the sister ship, the forces needed after the apex would follow it. If you changed the point where the astronaut started, the direction of forces needed prior to the apex would simply follow that as well. On a racetrack, this ideal direction will basically just follow the same angle as the track does at corner entry and exit.

It might be confusing to think if you are trying to get to the other ship in the shortest time possible that you would start out by trying to push yourself in a completely different direction. But remember, the astronaut starts his path going 100 mph already. If he does not immediately start slowing down and turning, he will fly past the apex out away from his goal and have to spend extra time coming back toward it.

It's important to understand this section and it might be worth rereading a few times and taking the time to think about it if necessary. While driving a racecar, it's very important to have a constant awareness of where the ideal direction is that you are trying to maximize acceleration. In the real world, the better a driver can generate and direct these forces with their vehicle to accomplish this, the lower their lap times will be and that's really at the heart of what this book is about and ultimately the core goal of Line Theory.

Of course, just telling a driver to go "generate some forces" doesn't really do much good on its own. As usual, the devil is in the details, but to understand the basic physics at work is helpful when trying to get an intuitive understanding of what you are really trying to accomplish on track. When trying to work through this book or trying to work up a particularly tricky section of track, it might be helpful to think back to this section. If you ever find yourself confused, just ask yourself, "What would the astronaut do?"

BACK ON EARTH

Okay, now we are well on our way to becoming a professional astronaut racer, but how does this help us down here on Earth where drivers need to worry about silly things like steering wheels and gravity. As it turns out, a car can actually mimic the actions of our astronaut quite well. While the astronaut just points his extinguisher and blasts away, a racecar driver would need to use his steering, brakes, and throttle to generate these same forces with the tires.

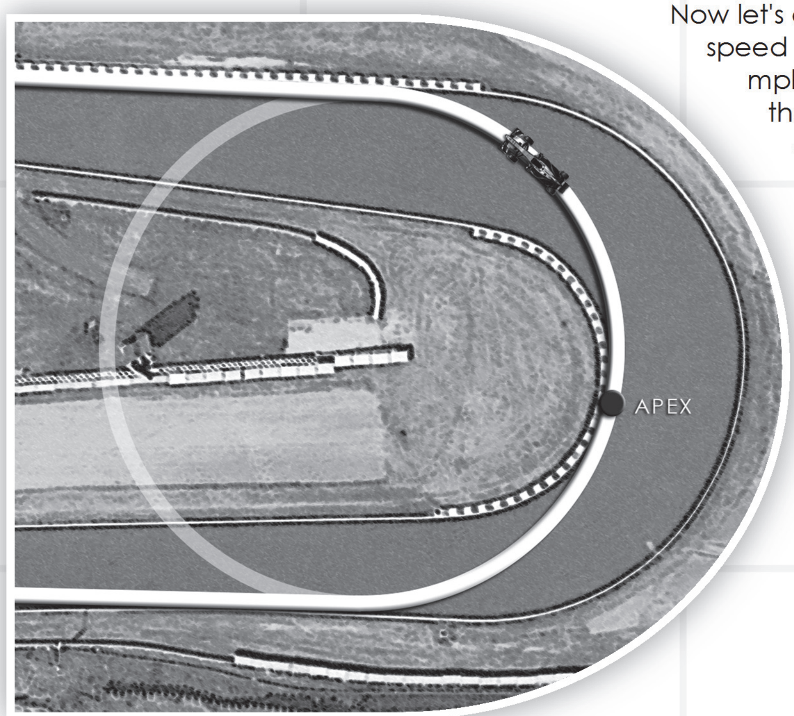
It's important to realize that the forces we talk about are ultimately generated at the tire/track interaction. For example, during corner exit, it's not really the engine that's generating the needed force, but the engine's ability to rotate the wheels in combination with the driver turning the steering wheel that generates the force from the tires. The driver not only has control over the total amount of force, but can also alter which way the forces are directed. The better a driver can maximize and direct these forces to mimic the actions of the astronaut the faster they will be able to complete a corner.

Let's work through this step by step as we learn what we are trying to accomplish in each section of a corner.

CORNER EXIT

It's always a debate whether to teach corner entry or corner exit first. It's natural to want to go in order, but we really can't go any further before first developing an understanding of what we are trying to achieve at corner exit and how everything revolves around the apex.

For our first example, let's look at the hairpin at Suzuka. Remembering that for any given radius, there is a maximum speed we can achieve, we'll put a car through the turn that on the limit can drive in a perfect circle at 50 mph. The white line represents the path of the car, but the shaded circle shows how the path of the car during the corner is completely circular.



Now let's drive the hairpin with a speed limiter in the car set to 50 mph so you just floor the throttle and drive a perfect circle along this line. We are still at the limit of traction of the tires; we just do not have any extra power to accelerate. This circular path causes the apex to be pretty close to the middle of the corner.

Take note that in this corner exit section we are going to be driving the beginning half of the corner in a perfect circle so we can more easily visualize the differences in speeds and angles at different apexes. This would require the driver held a basically constant steering wheel position and speed from corner entry to the apex. The car is still at the limit of traction though. As you'll see later, this is not the way you should optimally drive corner entry, but it helps with explanation and simplicity for now. A circular entry is also much easier from a car control standpoint so for a more novice driver it's not a bad approach as you improve your skills.

With the speed limiter on, there is no way to exit this corner any faster as we are generating the absolute maximum forward thrust possible. There is also no way to go faster at the apex by driving a bigger circle and still stay on track at corner exit unless you lifted off the throttle. This line is the optimum corner exit for the car right now.

While this circular corner exit would be optimized for a car driving with a speed limiter on, being able to apply more power at corner exit would get us to our goal faster and lower lap times. That should be fairly intuitive, but to understand exactly why from a physics standpoint let's look at what is happening from the viewpoint of our astronaut.

End of Sample

THE FINAL CORNER

It is our sincere hope that this book has helped to point you in the right direction, the ideal direction. You rarely see a happier face than one of a new driver at their first event. The ear-to-ear grin that comes with the simple pleasure of pushing a vehicle to its limits. We really hate to see that face turn to a scowl once the pursuit for an ever-lower lap time rears its fearsome head. The pursuit that sends many frustrated racers down countless dead ends in search of speed. But once you have completely digested and integrated the concepts taught in this book, we promise that simple pleasure of driving will return.

Eventually you will no longer see every corner as a completely separate puzzle with a unique answer. Once you truly begin to understand, you will see Line Theory fundamentals in every corner, in every car. Confusion will turn to confidence. The amazing fast laps you used to marvel at will turn into achievable goals. You just have to remember to always ask yourself…

"What would the astronaut do?"

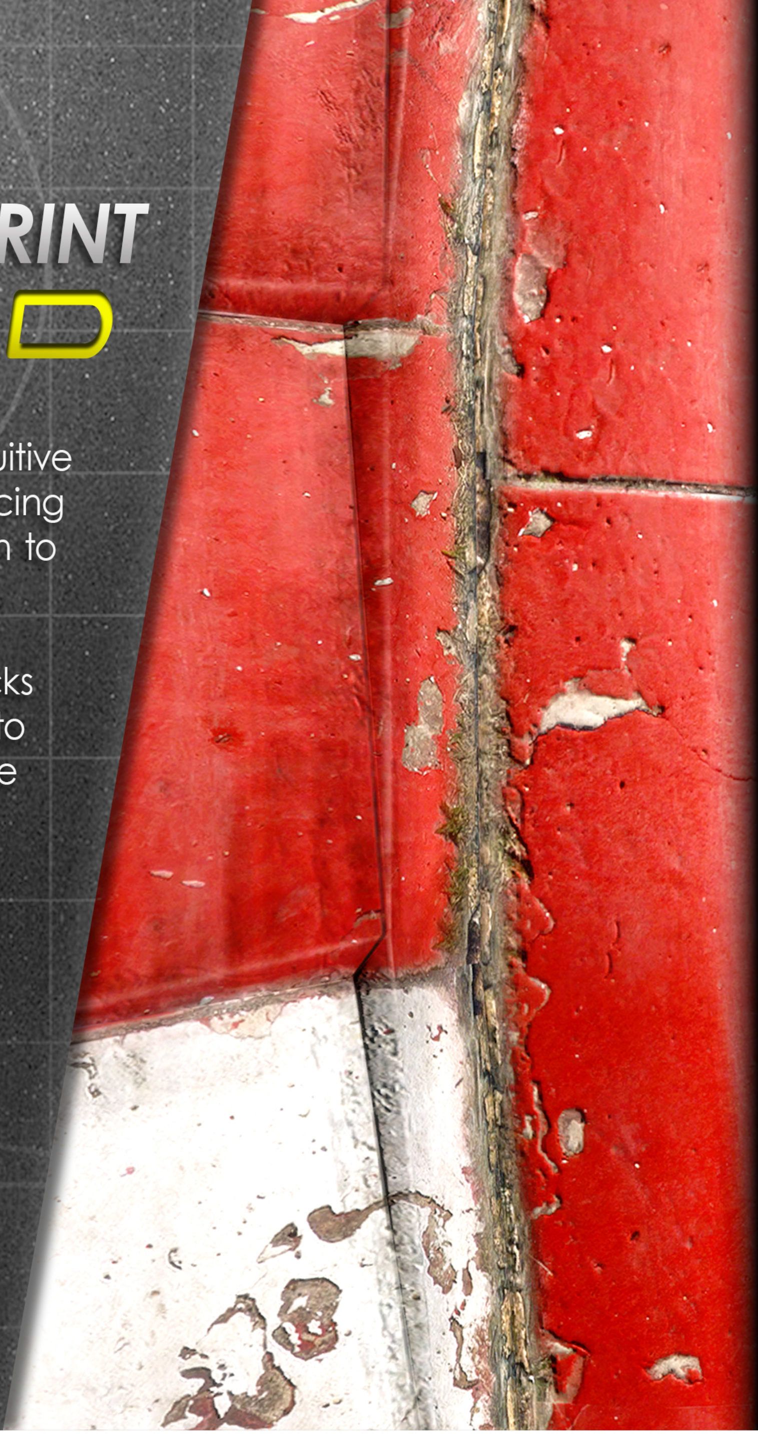
A DRIVER'S BLUEPRINT for SPEED

We will take you through an intuitive and fun lesson in the physics of racing and then we'll apply it as you learn to optimize your driving technique.

We will look at real-world racetracks and provide an exact procedure to find the ideal approach all from the driver's eye point of view.

Regardless of your current level of driving experience, you can apply these methods today and remove any doubt about what you should be doing on track for good.

PARADIGM · SHIFT
DRIVER DEVELOPMENT



Please visit us at **www.paradigmshiftracing.com**

ISBN 9781523441143

90000 >

9 781523 441143

$20.95