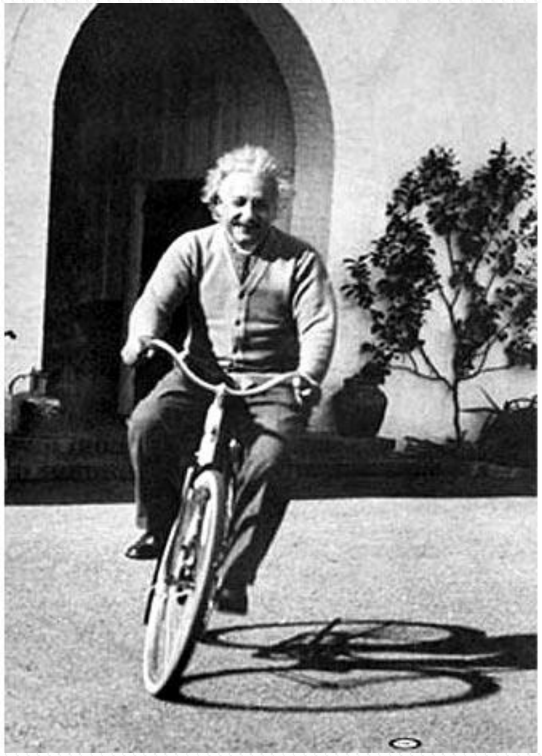


The Physics of Cycling

Why We Study The Bicyicle

- "The beauty of the bicycle resides in its sincerity. All its workings are open and visible." – J. Bertaut, 1936

- "[Bicycling] has done more for the emancipation of women than anything else in the world." – Susan B. Anthony, 1896

Bicycles Are Physics In Action

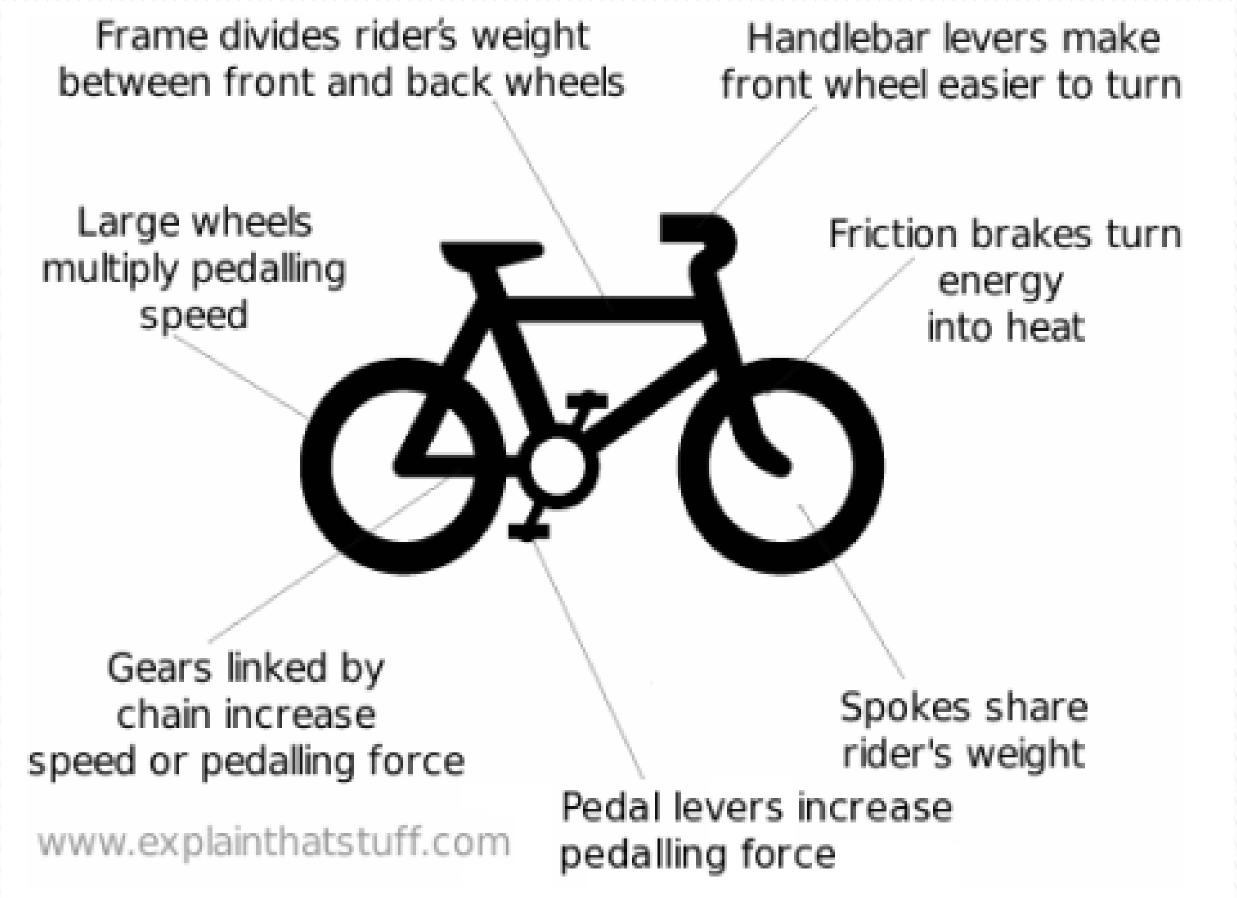


Image:scooter+physics.gif

The Science of Bicycles

- If you had to pick the greatest machine of all time, what would you say? If we were talking about machines that helped spread knowledge and educate people, you'd probably say the printing press. If we meant inventions that let people farm the land and feed their families, you might argue the plow or the tractor. If you think transportation is really important, you could go for the automobile engine, the steam engine, or the jet engine. But for its sheer simplicity, I would pick the bicycle. It's a perfect example of how pure, scientific ideas can be harnessed in a very practical piece of technology. Let's take a look at the science of cycles—and just what makes them so great!

Source: The Science of Bicycles, Chris Woodford, July 13, 2011

What's So Good About Bicycles?

- What's so good about the bicycle is that it can get you places quickly without gobbling up fossil fuels like gasoline, diesel, and coal or creating pollution. Bicycles can do this because they very efficiently convert the power our bodies produce into kinetic energy (energy of movement).

- Learn more at Woodford, Chris. "The Science of Bicycles." ExplainThatStuff.com/bicycles.html. July 31, 2013.

Air Resistance

For a racing bike traveling fast, about 80 percent of the work the cyclist does will go in overcoming air resistance, while the remainder will be used to battle rolling resistance; for a mountain biker going much more slowly over rough terrain, 80 percent of their energy goes in rolling resistance and only 20 percent is lost to drag.

Mathematical model of the physics of cycling

$$P_{TOT} = (P_{AT} + P_{KE} + P_{RR} + P_{WB} + P_{PE})/E_c$$

$$P_{TOT} = (0.5\rho V_a^2 V_g(C_d A + F_w) + 0.5(m_t + I/r^2)(V_{gf}^2 - V_{gi}^2)/(t_f - t_i) + V_g C_{rr} m_t g COS(TAN^{-1}(G_r)) + V_g(0.091+0.0087V_g) + V_g m_t g SIN(TAN^{-1}(G_r)))/E_c$$

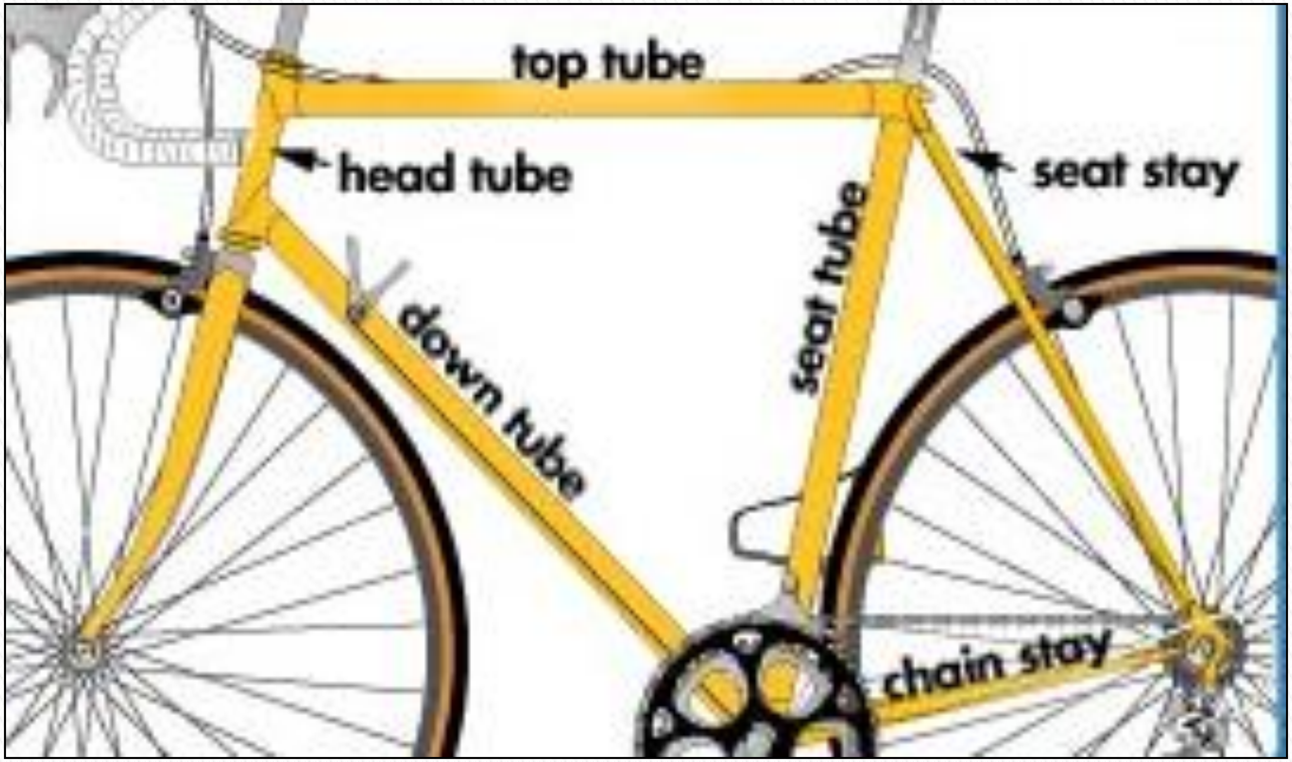
Where:

P_{TOT} = total power required (W)
P_{AT} = power required to overcome total aerodynamic drag (W)
P_{KE} = power required to change kinetic energy (W)
P_{RR} = power required to overcome rolling resistance (W)
P_{WB} = power required to overcome drag of wheel bearings (W)
P_{PE} = power required to change potential energy (W)
ρ = air density (kg/m^3)
V_a = air velocity (relative to direction of travel) (m/s)
V_g = ground velocity (m/s)
C_d = coefficient of drag (dependent on wind direction) (unitless)
A = frontal area of bike+rider system (m^2)
F_W = wheel rotation factor (expressed as incremental frontal area) (m^2)

m_t = total mass of bike+rider system (kg)
I = moment of inertia of wheels (kgm^2)
r = outside radius of tire (m)
V_{gf} = final ground velocity (m/s)
V_{gi} = initial ground velocity (m/s)
t_f = final time (s)
t_i = initial (s)
C_{rr} = coefficient of rolling resistance (unitless)
g = acceleration due to gravity (9.81 m/s^2)
G_r = road gradient (unitless)
E_c = efficiency of chain drive system (unitless)

(Martin, Milliken, Cobb, McFadden, and Coggan. J Appl Biomech 14:276-291, 1998)

The Frame and Materials



Courtesy of The Exploratorium. Used with permission.

Image: www.exploratorium.edu

How A Bicycle Frame Works

Assuming an adult weights 60–80 kg (130–180 lb), the frame of a bicycle has to be fairly tough if it's not going to snap or buckle the moment the rider climbs aboard. Ordinary bicycles have frames made from strong, inexpensive, tubular steel (literally, hollow steel tubes containing nothing but air) or lighter alloys based on steel or aluminum. Racing bicycles are more likely to be made from carbon-fiber composites, which are more expensive but stronger, lighter, and rustproof.

To learn more about how a bicycle works, please visit the Explain That Stuff website.

Innovative Frame Designs

The Oryx is a custom bike design made by Harald Cramer. This bike has a Y-frame shape which makes the bike shock proof. Well you might be wondering on how a person can sit on such a bike. Don't worry its not so difficult and its comfortable as well.

Innovative Frame Designs

Polygon Concept Bicycle: A great bicycle design and lifestyle. The Polygon Concept Bicycle was designed to rhyme with this comfortable lifestyle, it has a music player button attached to the steering, adjustable steering, it can convert kinetic energy into power and automatically store it in the battery which can be used for tail light at night.

Read more: http://limcorp.net/2009/creative-bicycles-designs#ixzz1pIPGAAj8a

Innovative Frame Designs

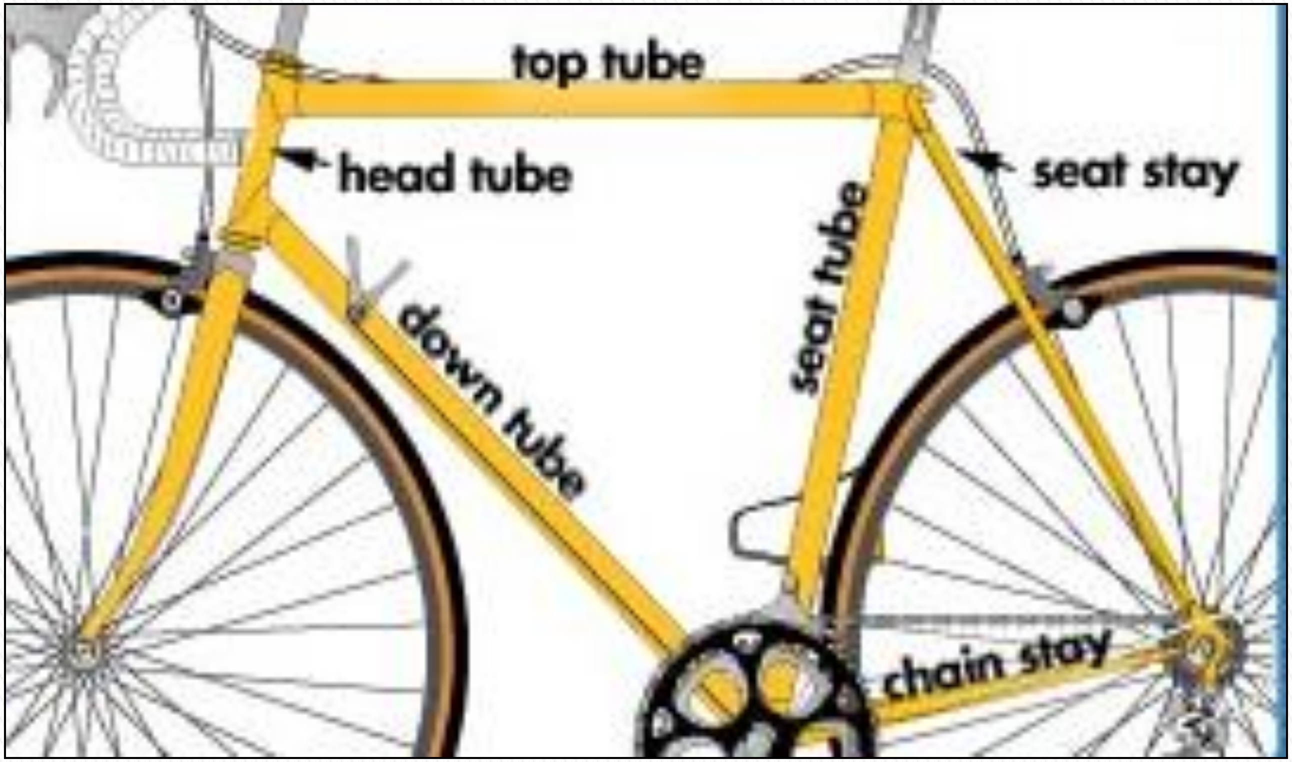
Innovative Frame Designs

Innovative Frame Designs

Nicola Guida is an Italian designer who created this racing frame for Picchio, a small manufacturer of racing cars based in Ancarano, Italy. The bike design was his final student project and Picchio helped him out with the construction of a prototype.

image: courtesy of bicycledesign.net

The Frame and Materials



Courtesy of The Exploratorium. Used with permission.

Image: www.exploratorium.edu

Innovative Frame Designs

This organic, curvy, hubless rendered bike concept by Chinese designer Liu Chien Sheng is far from minimalist or traditional. This one is really just a styling exercise with many construction issues that would need to be addressed if it were to be prototype.

Learn more at the Reality Distorted blog.

The Wheel

The wheels on these bicycles were made of steel but lacked pneumatic tires (with the possible exception of the boy's bike). Some bikes made for small children are still made with solid tires. This photograph was taken around 1910.

To learn more about wheels, visit the Exploratorium's website.

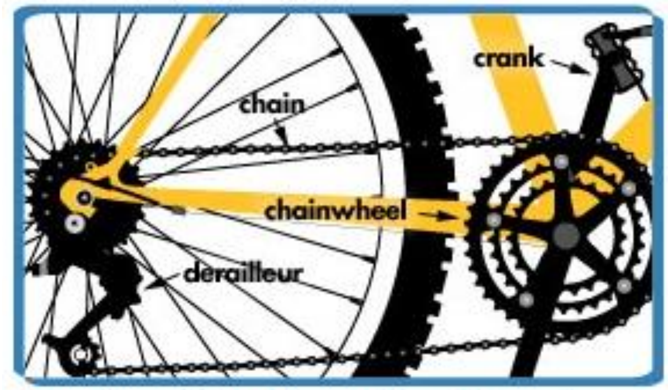
Time Marches On!

- The pneumatic tire and the chain drive, followed by the development of gears, revolutionized bicycling in the later 1800s.

To learn more about pneumatic tires, visit the Exploratorium's website.

Drives and Gears

The development of the chain drive helped make the bicycle that we know today possible. The chain drive eliminated the need to have the cyclist directly above the wheel. Instead, the cyclist could be positioned between the two wheels for better balance. With the advent of gears, the cyclist could also pedal more efficiently. Riders enjoyed increased speed and easier riding up steep grades.



A modern chain drive and derailleur system.

Read more about drives and gears on the Exploratorium's website.

Drives and Gears: Torque

Torque is what makes the wheels on the bicycle go around. A great deal of research has been done to determine how to increase the torque applied by the rider to the rear wheel, while decreasing the torque required to make the wheels on a bicycle turn.

The series of parts that drive the bicycle forward are called the *drive train*.

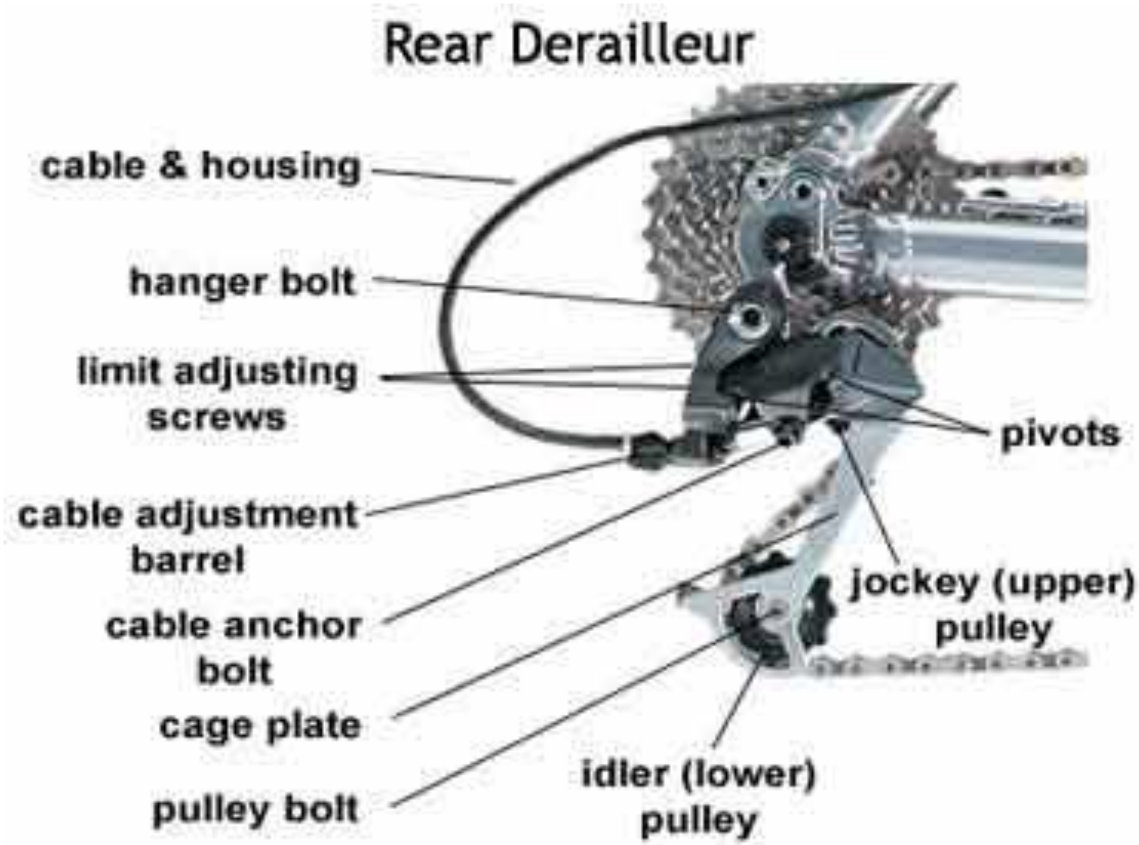
The torque produced by the drive train is dependent upon the size of the chain ring (the large gears mounted on the crank) being used, and the size of the rear cog being used. When the chain is on the smaller chain ring, the force applied through the chain must be greater because the chain ring is closer to the axis of rotation and must apply a larger force to equal the torque produced by the pedals.

Gear Ratios

The Gear Ratio is the relationship between the number of teeth on two gears that are meshed or two cogs that are connected by a common roller chain.

To l earn more about gears, visit the Exploratorium's website.

How Bicycle Gears Work



Fixed Gear Bike Study

Tongue in cheek study showing correlation between high school physics grades and the number of experiences riding a fixed gear bicycle coming to the conclusion that those who went so far as to own a fixed gear bicycle had no hope of passing their next physics exam. The data suggest that a weak understanding of momentum and properties of moving bodies more generally as measured by high school physics grades is positively associates with how many times one has ridden a fixed gear bike.

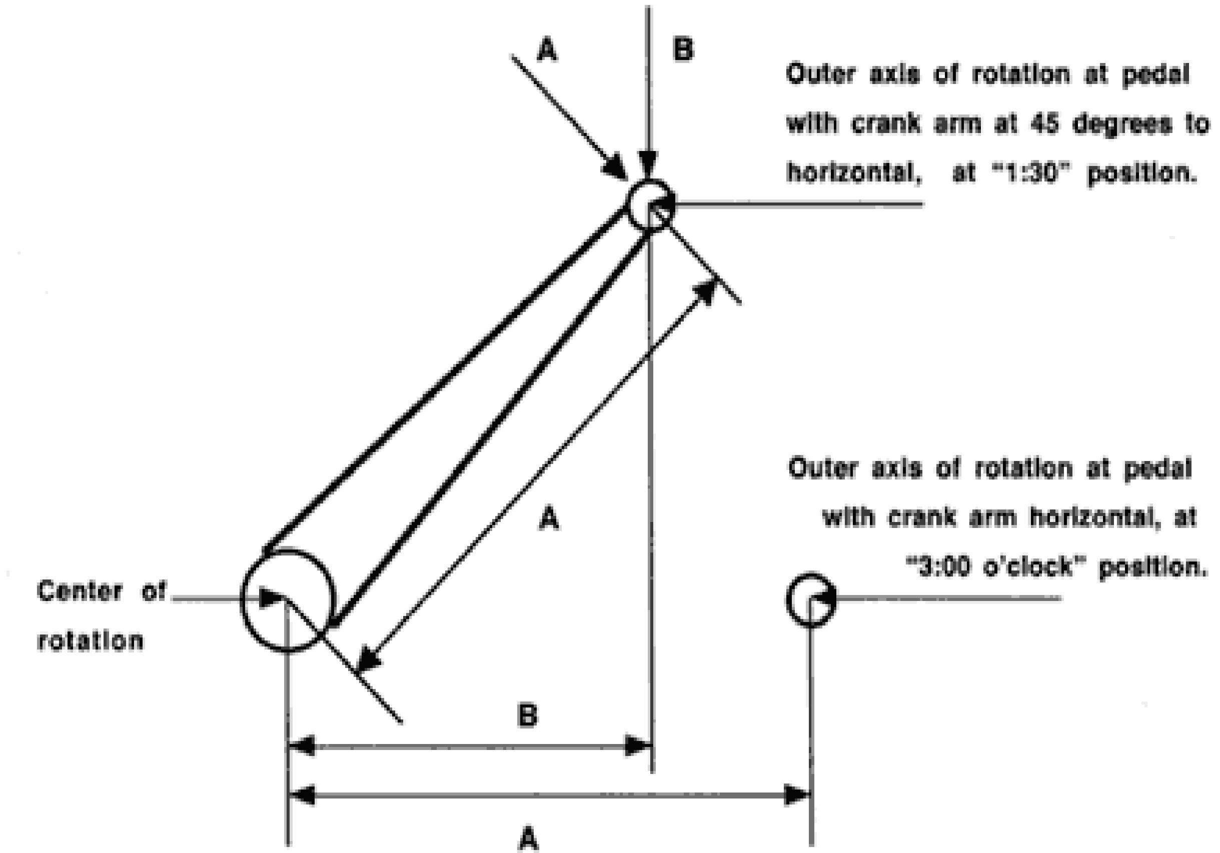
See related graph.

Proper Pedaling Technique

You can pedal a bike well enough to get by, or you can pedal a bike efficiently and get the most out of the incredible mechanical advantage that's available.

Read more on the Bike/Split website.

Proper Pedaling Technique



Courtesy of Bike/Split. Used with permission.

Source: wwwbikesplit.com

Breaking and Steering

Brakes have improved as materials and engineering know-how have evolved. The earliest bicycles lacked brakes, which added to their daredevil reputation.

Read more about braking and steering on the Exploratorium's website.

How Bicycle Brakes Work

No matter how fast you go,

there comes a time when you

need to stop. Bicycle brakes work on a principle of basic physics: *friction* (the rubbing force between two things that slide past one another while they're touching). When you press the brake levers, a pair of rubber or composite shoes clamp onto an inner surface of the front and back wheels. As the brake shoes rub tightly against the braking surface, they turn kinetic energy (the energy you have because you're going along) into heat—which has the desired effect of slowing you down.

The Coaster Brake

Image removed due to copyright restrictions.
View an image of a coaster brake.

The coaster brake is still in wide use throughout the world and appears in a number of less sophisticated bicycles like cruisers and utility bicycles.

Coaster brakes also appear on some children's bicycles and tricycles. The coaster brake works by reversing the motion on the pedals. The brake mechanism is inside the hub of the wheel and pushes outward on the hub, creating friction and slowing the bike. This brake is particularly strong and tends to "lock up" or skid the rear wheel when engaged.

Caliper Brakes

Read about caliper brakes on the Exploratorium's website.

Disc Brakes

Courtesy of High Ball Blog. Used with permission.

A disc brake consists of a metal disc attached to the wheel hub that rotates with the wheel. The advantage is that they perform equally well in all conditions. Disc brakes are better than rim brakes because of a very simple principle of physics: it is easier to stop a slower moving object than it is to bring to a halt an object moving at high velocity.

image courtesy of highballblog.com

Hydraulic Brakes

The newest innovation in high-end bicycles is the hydraulic brake. Hydraulic brakes work on the principle of hydraulic pressure. The brake lever is used to push fluid (usually mineral oil or DOT fluid) from a reservoir through a hose to move pistons in a caliper thus forcing pads against the braking surface. Pushing from that central bolt is a small piston that pushes a cam to split the arms and bring the pads to the rims. The resulting braking power is stronger and easier to modulate. From an aerodynamic standpoint, it brings everything in closer and directly in front of the frame, a benefit to any bike, and there's no cable sticking off to the side.

image:Magura RT8 TT

How to Brake a Bicycle: Balance

When braking a bicycle, balancing the braking between the front and rear tire is very important. The most important things about stopping are that you want to stop quickly, in control, and not go over the handlebars. As you go along on the bicycle and apply the brakes, your body has inertia so it has a tendency to continue its forward momentum. That shifts your weight forward onto the front wheel. So, many riders do a lot of braking with the front wheel, but if you do too much braking with the front wheel, you can wind up going over the handlebars. So the idea of the braking the bicycle is to balance the braking between the front and the back to get the maximum braking.

How To Brake A Bicycle: Think Ahead

In addition to balance, thinking and planning ahead is key to effective and safe braking. One of the reasons competitive cyclists pre-ride the courses is so they can plan braking. The proper technique for braking on sharp turns is to brake ahead of the corner, and as you go through the corner release the front brake and only use the rear brake.

Wind Resistance

Every bicyclist has to overcome wind resistance. Most recreational bicycles in which the rider sits upright have very poor aerodynamics. While newer bicycles are being designed with better aerodynamics in mind, the human body is simply not well designed to slice through the air. Bicycle racers are aware of the problem of wind resistance and over the years have developed techniques for minimizing its effects. Bicycle designers and inventors are constantly tinkering with bicycle designs and shapes, the size and shapes of wheels and the designs of helmets and clothing looking for improvements in aerodynamic performance.

The Steamline Position

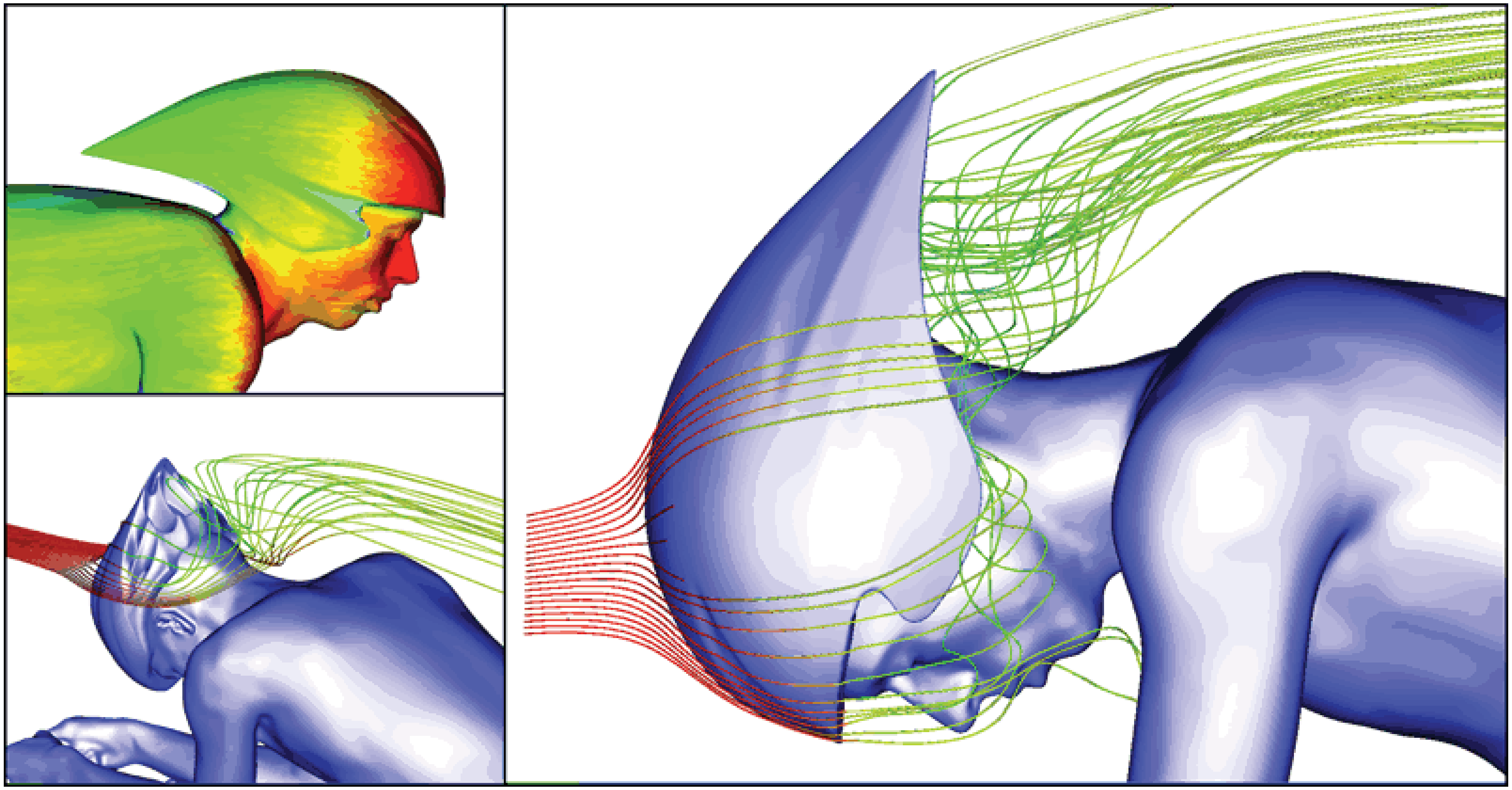
The handlebars of a bicycle are levers: longer handlebars provide leverage that makes it easier to swivel the front wheel. But the wider the arms of the cyclist are spaced, the more air resistance is created. That's why racing bicycles have two sets of handlebars to help the cyclist adopt the optimal streamlined position. There are conventional, outer handlebars for steering and inner ones for holding onto on the straight. Using these inner handlebars forces the cyclist's arms into a much tighter, more streamlined position. Most cyclists now wear aerodynamically shaped helmets for improved aerodynamics

Wind Resistance

Every cyclist who has ever pedaled into a stiff headwind knows about wind resistance. It's exhausting!

Read more about wind resistance on the Exploratorium's website.

Aerodynamic Drag

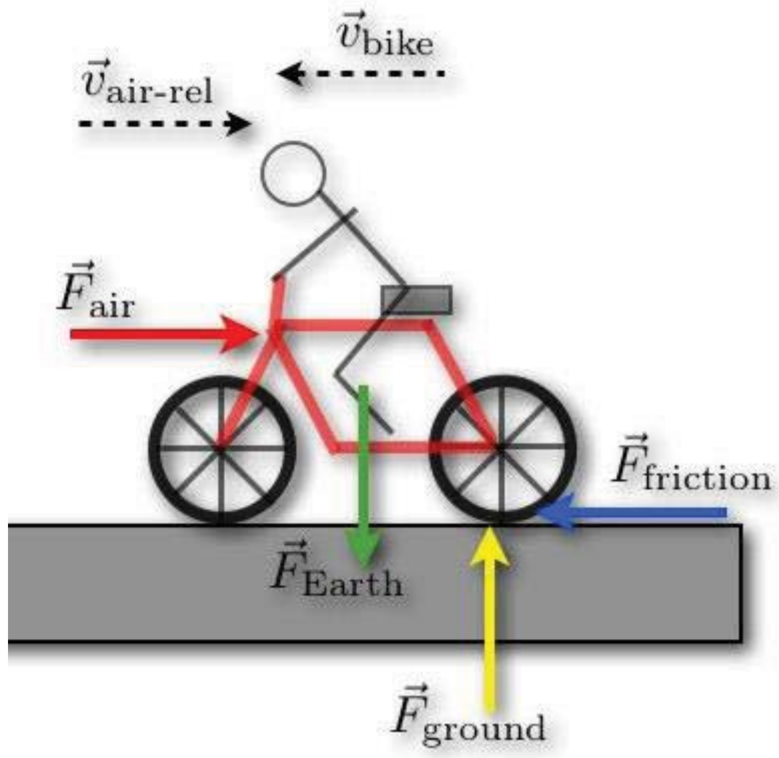


Computational Fluid Dynamics (CFD) uses a computer program to graphically illustrate fluid dynamics.

Speed Is Limited by Friction.

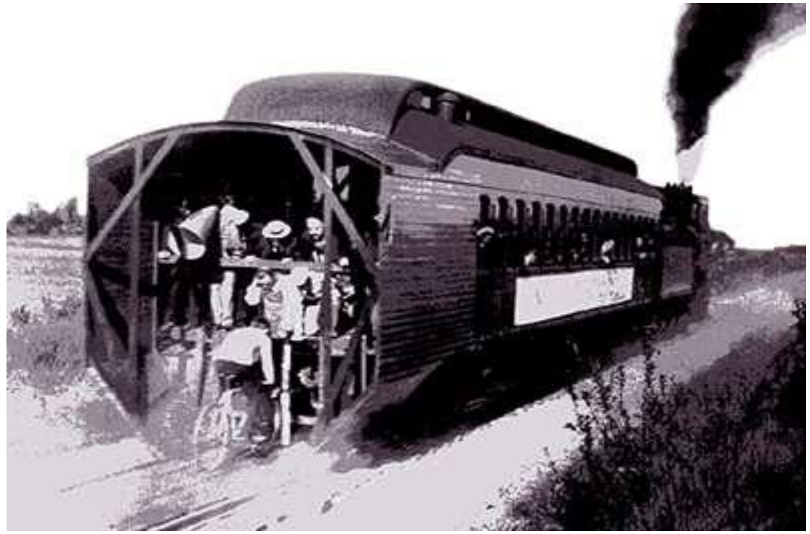
- Above ten miles an hour, air friction dominates.
- An amateur cyclist can produce a steady state of about 225Watts (Like two 100W light bulbs).
- Peak to 300Watts for a few minutes.
- Max out at 350-400Watts for brief spurts.
- A Professional bicyclist can produce about twice that amount or about 400-500Watts at a steady rate.
- The untrained cyclist can produce about half the amount of a trained amateur or about 100Watts.
- Drafting to beat air resistance.
- Stay within 1ft of leading wheel

Wind Resistance



Courtesy of Rhett Allain. Used with permission.

Wind Resistance



Charley "Mile-a-Minute" Murphy was an early cycling racer. His "mile-a-minute" feat was accomplished in 1899. At that time he traveled faster than the fastest automobile. Notice the large windscreen on the train in front of him which greatly reduced wind resistance.

Aerodynamic Drag

On a flat road, aerodynamic drag is by far the greatest barrier to a cyclist's speed, accounting for 70 to 90 percent of the resistance felt when pedaling. The only greater obstacle is climbing up a hill: the effort needed to pedal a bike uphill against the force of gravity outweighs the effect of wind resistance.

Read more about aerodynamic drag on the Exploratorium's website.

Aerodynamic Shapes

Modern bicycles are offered in a wide array of shapes and sizes. Most fit into one of three categories: standard, or double-diamond, made from standard-sized round tubing; semi-aero, a double-diamond style with the addition of airfoil-shaped tubes; and full-aero, constructed with all airfoil-shaped tubes with or without alternative frame shapes to the conventional double-diamond shape, according to Asker E. Jeukendrup, editor of the book "High Performance Cycling.“

Why Clothing Matters

Friction is a great thing in brakes and tires—but it's less welcome in another form: as air resistance that slows you down. The faster you go, the more drag becomes a problem. At high speeds, racing a bicycle can feel like swimming through water: you can really feel the air pushing against you and you use approximately 80 percent of your energy overcoming drag. A bicycle can be narrow and streamlined, but a cyclist's body is much fatter and wider. In practice, a cyclist's body creates more than twice the amount of drag as the bicycle. That's why cyclists wear tight neoprene clothing and pointed helmets to streamline themselves and minimize energy losses.

Human Power

The bicycle is a tremendously efficient means of transportation. In fact, cycling is more efficient than any other method of travel--including walking!

Read more about Human Power on the Exploratorium's website.

Muscle Recruitment

- Thousands of thin spaghetti-like fibers make up muscle tissue. These fibers receive messages from the brain, causing the fibers to contract.

Read more about how muscles work on the Exploratoriun's website.

Power

- Lactate (energy)
- Musculoskeletal (muscles)
- Cardiovascular (Heart and breathing)
- 3 power systems
  - Creatine Phosphates (<10s)
  - Glycolosis (Anerobic) (10s – 2min)
  - Citric Acid Cycle (Aerobic) > 2min

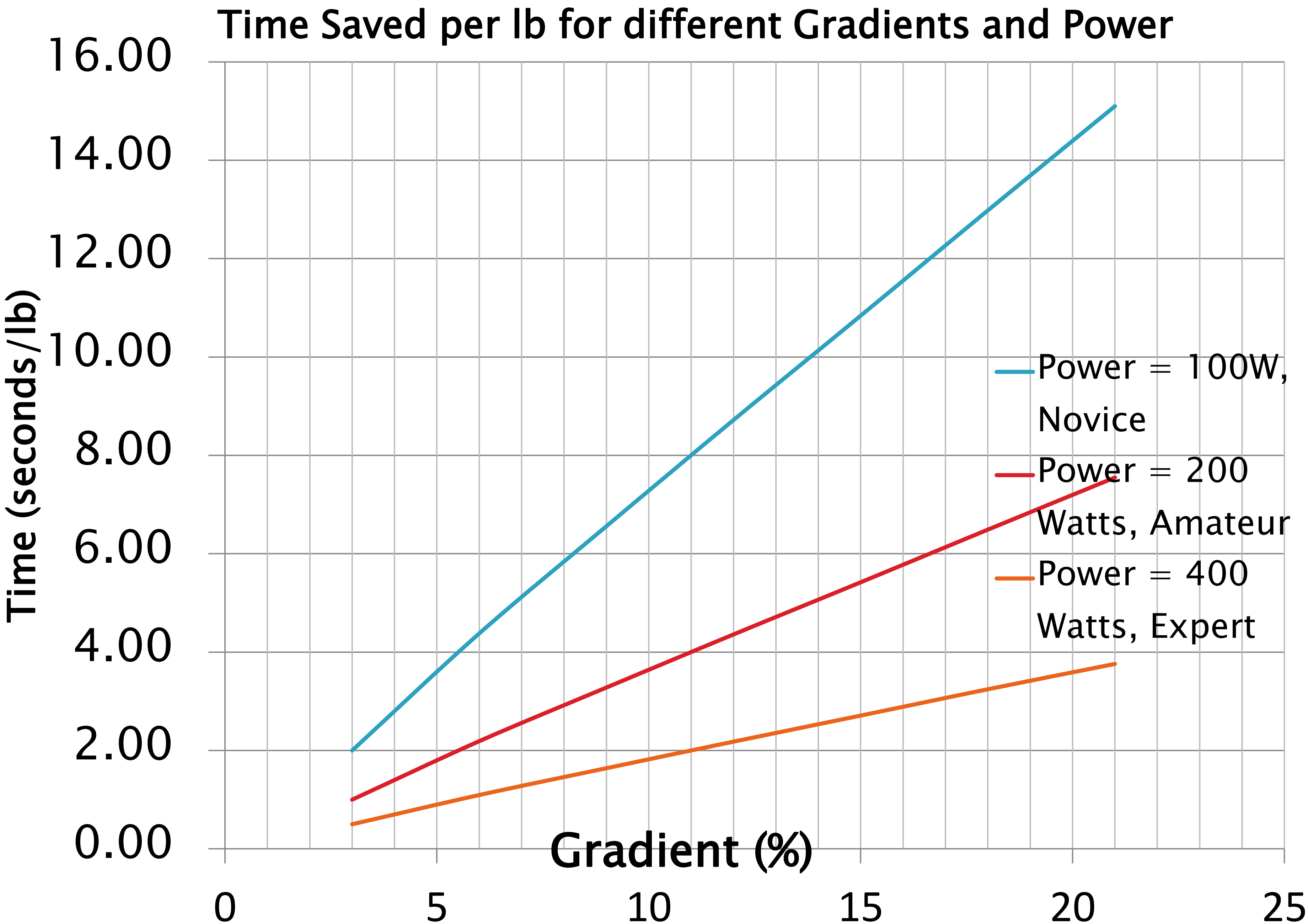
Discussion & Analysis

- How does weight affect time on a climb?
- Braking – How slow should you go when its wet?
- Turning – The safest turn (and fastest)
  - Look ahead in the turn, bike goes where you look
  - Brake before turn, Feather only in turn
  - Lean bike, not body (Center of mass)
- Friction, Braking and Turning
- Short and Sweet Physics Answers

How Much of an Effect Does Weight Have?

- Basic Equation: Power = (Weight x Height)/Time
  - Time = Weight x Height/ Power
  - To save time: Increase power or lose weight
  - But How Much?
- How much time saved per.....
  - Pound of weight (person or bike)
  - Gradient (Watershed vs. Paris Mountain)
  - Watts produced

http://www.analyticcycling.com



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Understanding Friction

- Friction force between tires and road
  - Prevents slipping
- Friction can be used for turning, accelerating, braking, or some combination
- Examples:
  - Downhill turns: 50% braking, 50% turning = 100% available friction!
  - Uphill turn: 50% turning = 50% available friction
  - Criterium turn: 60% turning, 20% acceleration= 80% total friction
- Greater than 100% -> sliding->Crash!

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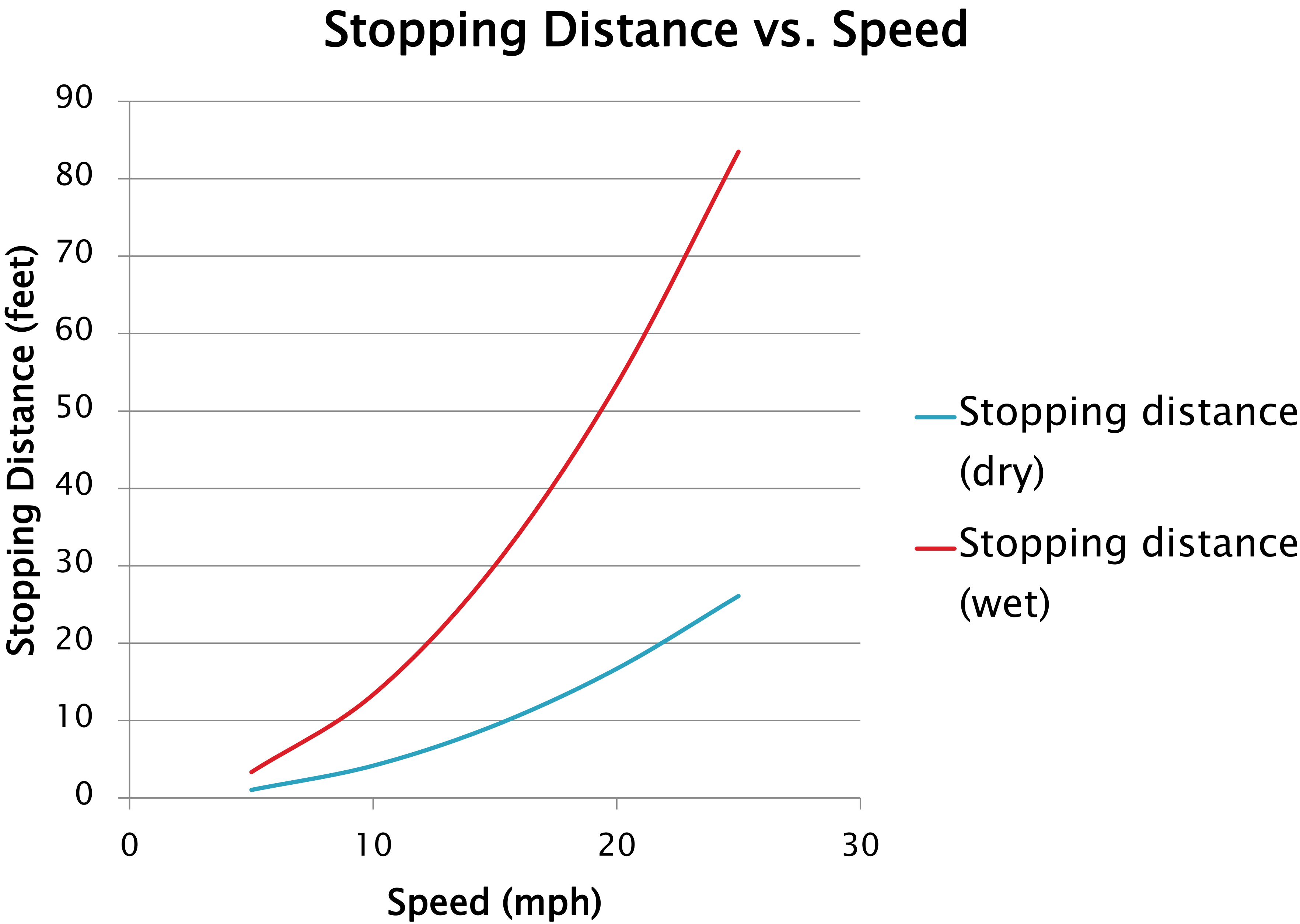
Stopping Distances

- Stopping Distance =
  - Speed^2/(2 x coefficient of friction x gravity)
- To decrease distance...
  - Need more friction or less speed



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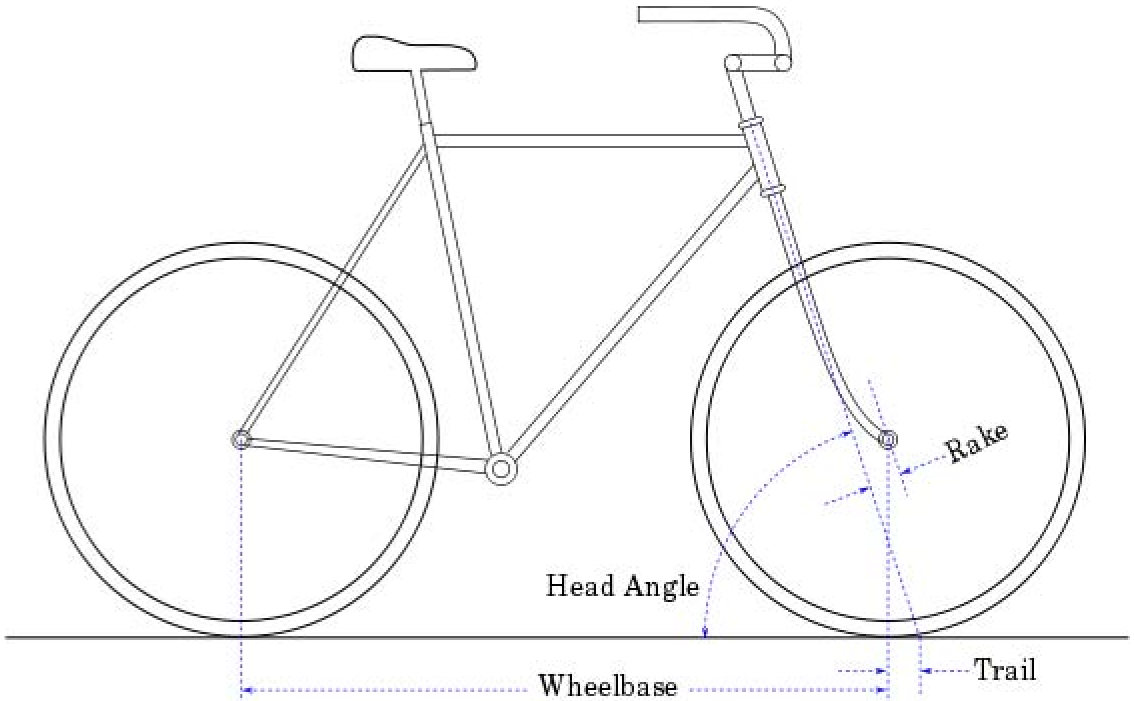
Bicycle Frame Geometry: Rake and Trail



Bicycle Frame Geometry: Wheelbase

Wheelbase is the horizontal distance between the centers (or the ground contact points) of the front and rear wheels. Wheelbase is a function of rear frame length, steering axis angle, and fork offset. It is similar to the term wheelbase used for automobiles and trains.

Wheelbase has a major influence on the longitudinal stability of a bike, along with the height of the center of mass of the combined bike and rider. Short bikes are much more likely to perform “wheelies” and “stoppies”.

Courtesy of "Bicycle and motorcycle geometry." on Wikipedia.

Bicycle Frame Geometry: Fork Offset

Required rake angle arose from early times when lightweight bicycles suffered fork failures from road shock. Most fatigue failures of forks result in a fork blade breaking at the rear edge of the fork crown from repeated vertical road shocks. Before most roads were paved, fork rake had a lower angle so the fork would be loaded axially on rougher surfaces. As most roads became paved, bicycles forks were made steeper, which also gave lighter steering.

Bicycle Frame Geometry: Rake and Trail

Bicycle forks usually have an offset, or rake, that places the fork ends forward of the steering axis. This is achieved by curving the blades forward, angling straight blades forward, or by placing the fork ends forward of the centerline of the blades. The latter is used in suspension forks that must have straight blades in order for the suspension mechanism to work. Curved fork blades can also provide some shock absorption.

Bicycle Frame Geometry: Rake and Trail

The purpose of this offset is to reduce 'trail', the distance that the front wheel ground contact point trails behind the point where the steering axis intersects the ground. Too much trail makes a bicycle feel difficult to turn.

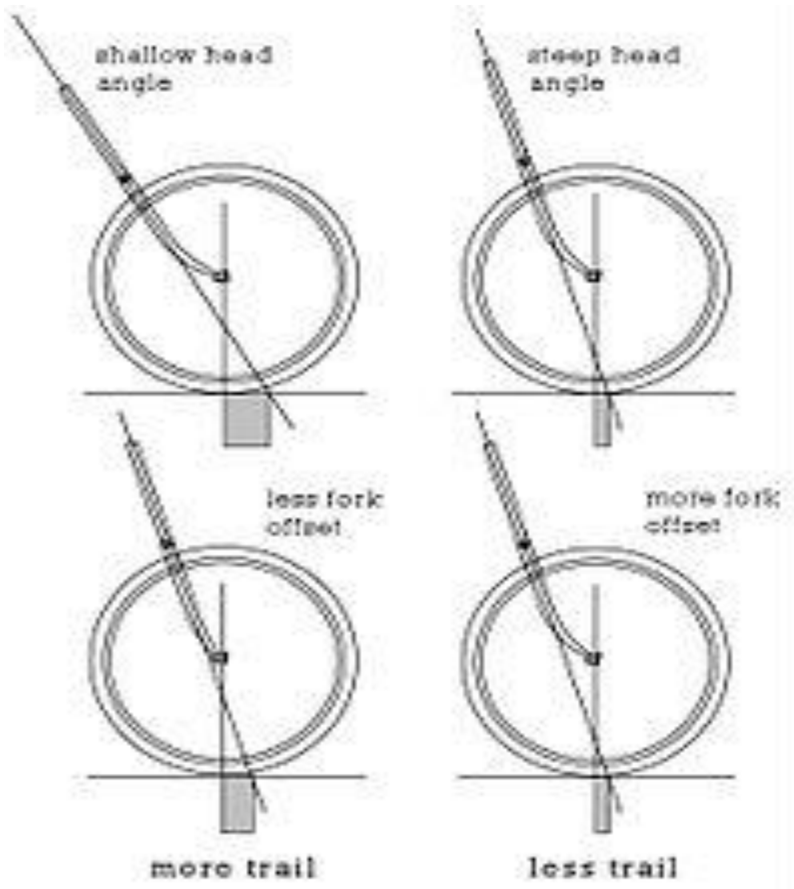
Bicycle Frame Geometry: Rake and Trail

Road racing bicycle forks have an offset of 40–45mm. For touring bicycles and other designs, the frame's head angle and wheel size must be taken into account when determining offset, and there is a narrow range of acceptable offsets to give good handling characteristics. The general rule is that a slacker head angle requires a fork with more offset, and small wheels require less offset than large wheels.

Bicycle Frame Geometry: Rake and Trail

Fork offset influences geometric trail, which affects a bicycle's handling characteristics. Increasing offset results in decreased trail, while decreasing offset results in increased trail.

Bicycle Frame Geometry: Rake and Trail



Bicycle Frame Geometry: Trail and Caster

Trail, or caster, is the horizontal distance from where the steering axis intersects the ground to where the front wheel touches the ground. The measurement is considered positive if the front wheel ground contact point is behind (towards the rear of the bike) the steering axis intersection with the ground. Most bikes have positive trail, though a few, such as the two-mass-skate bicycle and the Python Lowracer have negative trail.

Bicycle Frame Geometry: Trail and Caster

Trail is often cited as an important determinant of bicycle handling characteristics and is sometimes listed in bicycle manufacturers' geometry data, although Wilson and Papodopoulos argue that mechanical trail may be a more important and informative variable.

Bicycle Frame Geometry: Trail and Caster

Trail is a function of head angle, fork offset or rake, and wheel size. Their relationship can be described by this formula:

$$\text{Trail} = \frac{Rw\cos(Ah) - Of}{\sin(Ah)}$$

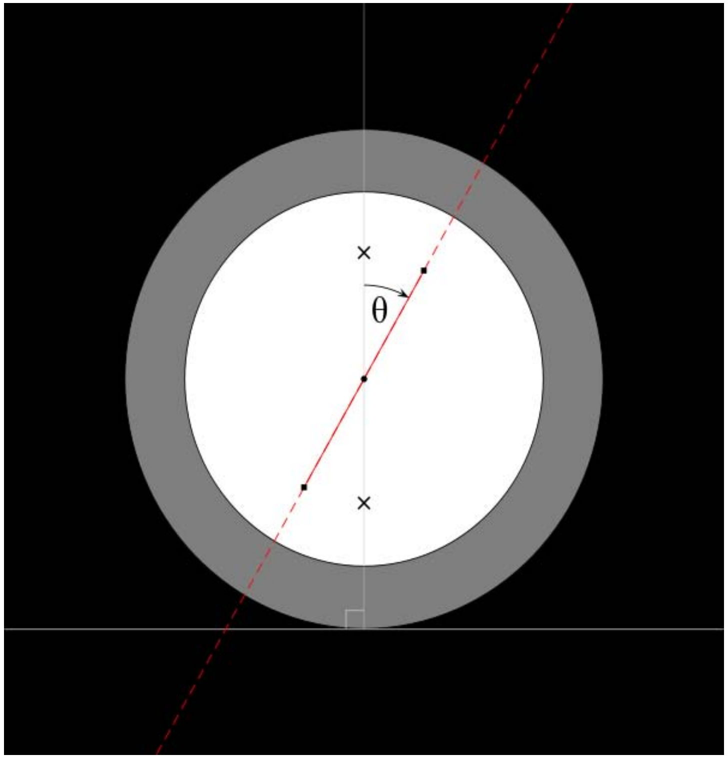
where *Rw* wheel radius, *Ah* is the head angle measured clock-wise from the horizontal and *Of* is the fork offset or rake.

Bicycle Frame Geometry: Trail and Caster

Trail can be increased by increasing the wheel size, decreasing or slackening the head angle, or decreasing the fork rake or offset. Trail decreases as head angle increases (becomes steeper), as fork offset increases, or as wheel diameter decreases

Castering

Castering or Caster Angle:
Is the angular displacement from the vertical axis of the suspension of the steered wheel measured in the longitudinal direction. It is the angle between the pivot line and vertical.



Turning & Cornering

Image courtesy of Eugene Wei on Flickr. CC BY-NC-SA

- Friction allows you to turn
- F = m x a,
  - or Friction = mass x acceleration
- Friction = μ x Weight , kind of
  - μ – friction coefficient due to surface (asphalt, concrete, etc)

Math Magic...

Radius of turn = speed^2 / μxg

- Must have bigger radius to go faster
- Or must have more friction

Amount of Trail/Rake

- Short Trail: quick handling, feel road imperfections. Racing and road bikes, generally expensive bikes.
- Medium Trail: intermediate response, some insulation from road. Mountain and touring bikes.
- Long Trail: sluggish response, insulates entirely from road. Feels easier, but actually harder. Cheap "department store bikes“
- Counter Steering

Turning and Cornering

- Most physicists think than angular momentum is the wheel is responsible for balancing. In fact, angular momentum has very little to do with the way a bicycle behaves.

- Centrifugal forces will throw your bike over on its side if you steer the handlebars in the direction of the desired turn without first leaning the bike into the turn. Leaning the bike into the turn allows gravitational forces to balance the centrifugal forces, leading to a controlled and stable turn.

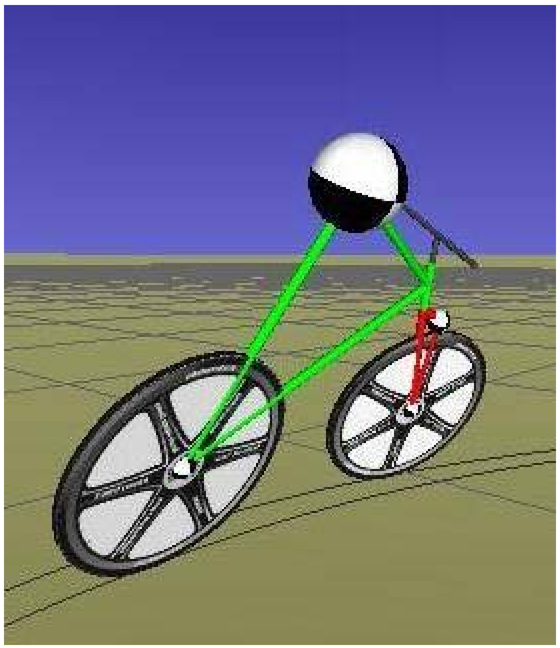
- Thus: (Gyroscopic Torque) + (Moment of Inertia of Wheel Around Steering Axis x Acceleration of the Steering Angle) = (Aplied Torque on Handlebars) – (Trail-Steering) – (Castering)

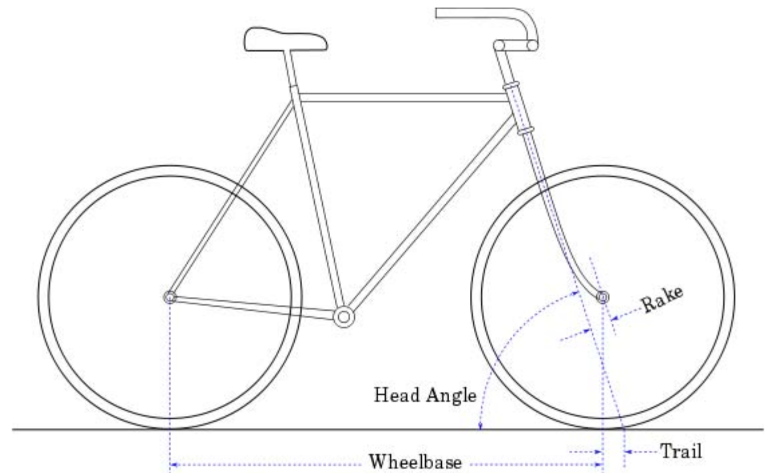
Countersteering

One method of establishing the proper lean is *countersteering*, i.e., explicitly turning the handlebars counter to the desired turn thereby generating centrifugal torque which leans the bicycle appropriately.

Learn more by reading the article, Fajans, J. "Steering in Bicycles and Motorcycles." American Association of Physics Teachers, 2000.

Turning Stability – Front Fork

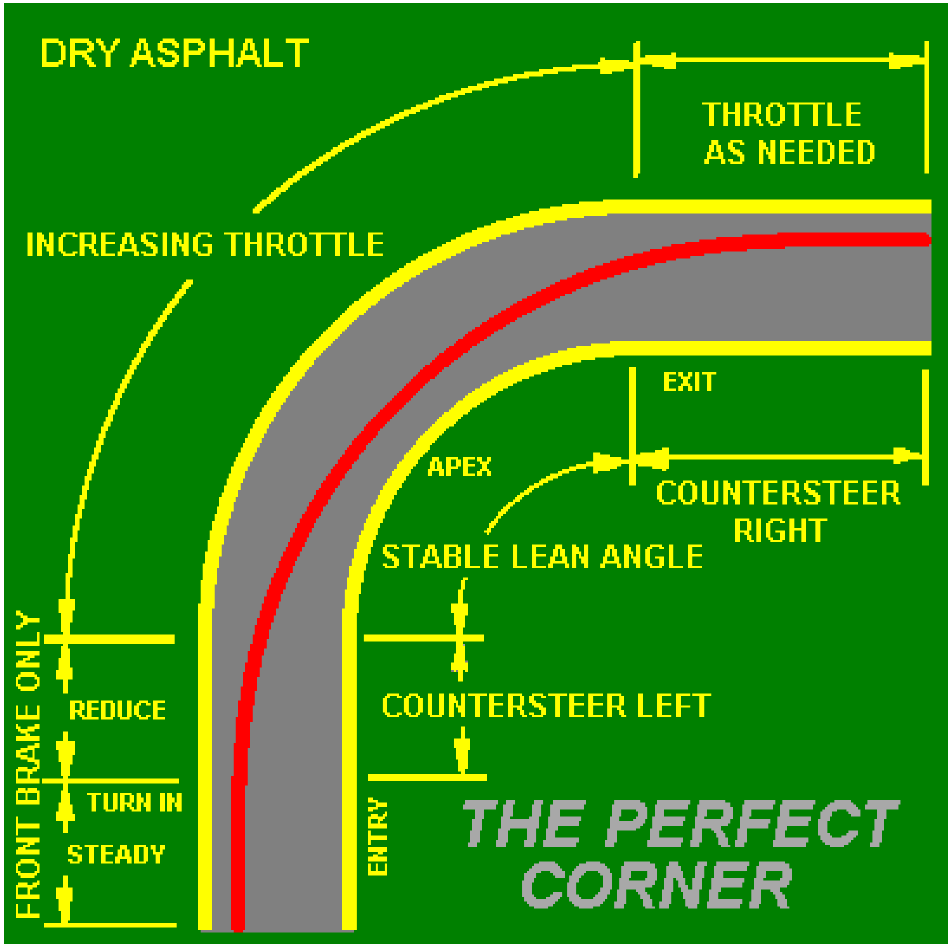




Turning Tips

- Slow down BEFORE YOU TURN
- Brake In A Straight Line
- Only Feather Brakes In Turn If Needed
- Look Through The Turn For The Apex

Turns


DRY ASPHALT
THROTTLE AS NEEDED
INCREASING THROTTLE
EXIT
APEX
COUNTERSTEER RIGHT
STABLE LEAN ANGLE
FRONT BRAKE ONLY
REDUCE
TURN IN
STEADY
COUNTERSTEER LEFT
ENTRY
THE PERFECT CORNER

Turn Examples

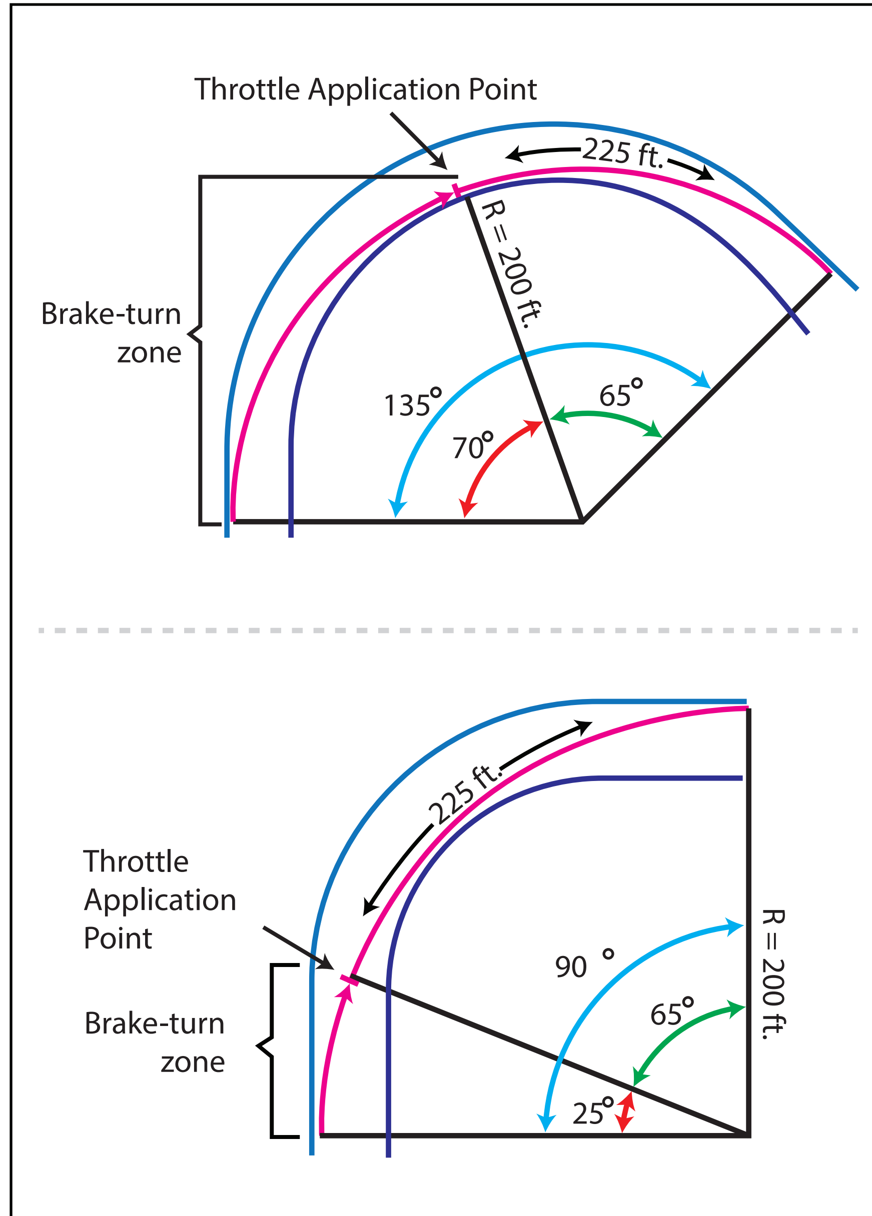
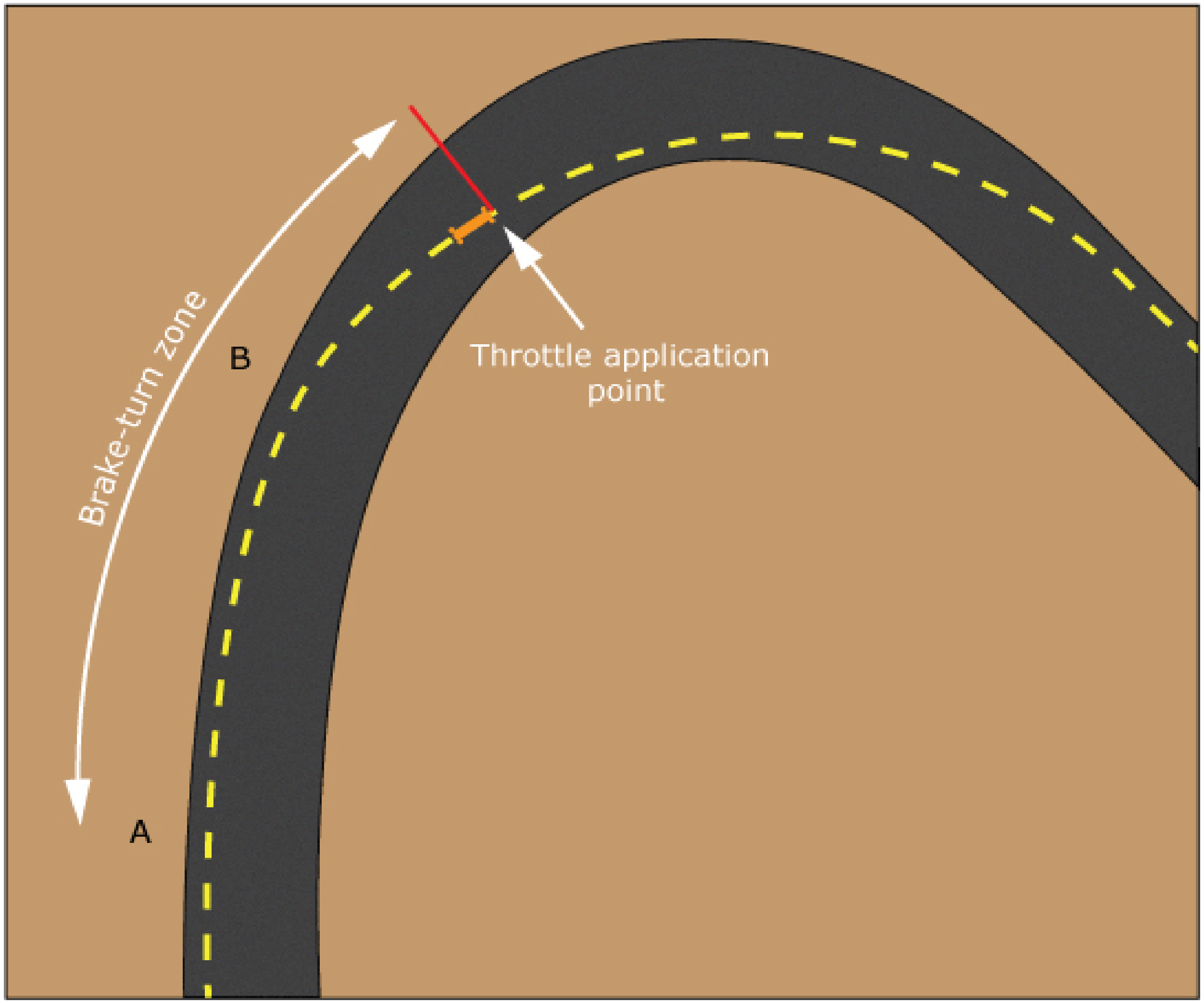


Image by MIT OpenCourseWare.

Turn Examples



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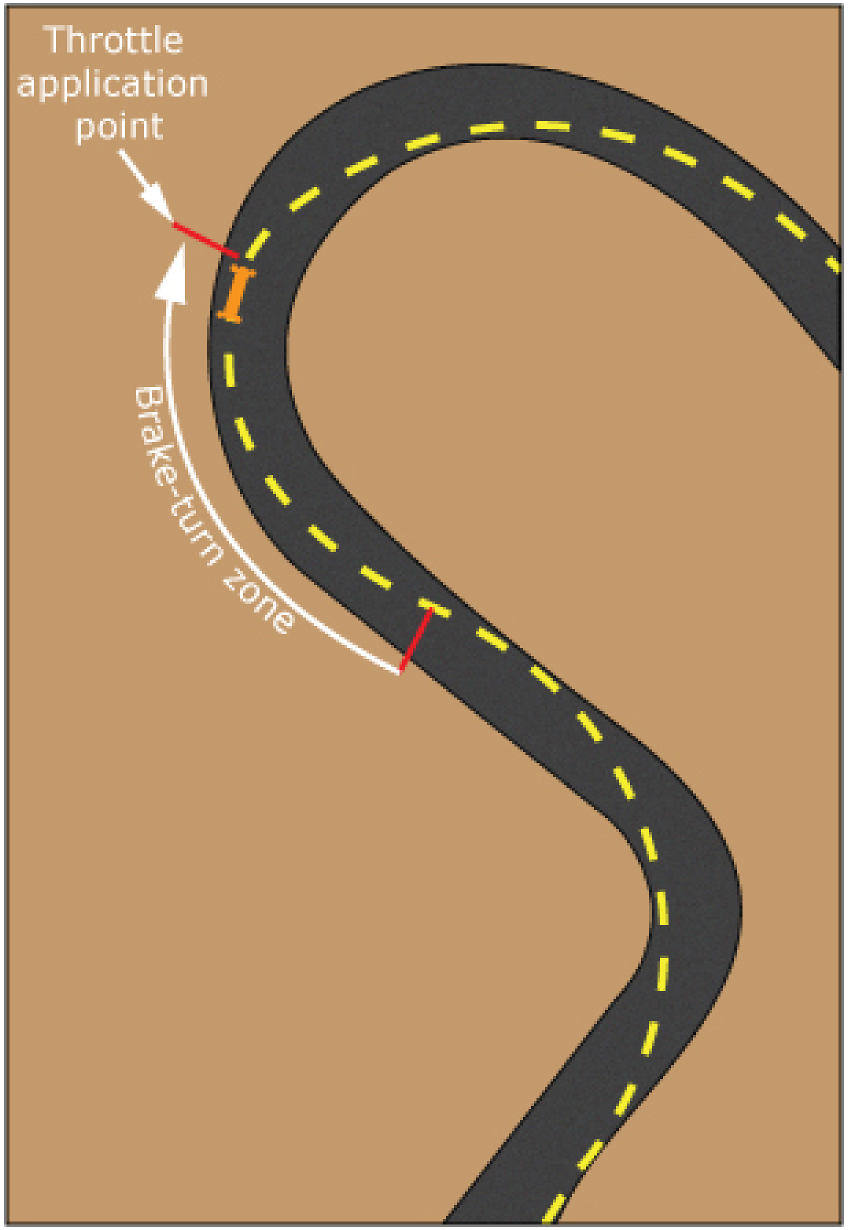
Turn Examples



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Free Speed

- Aerodynamics
- Seat adjustment
- Pedal Stroke and Muscle Recruitment

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