THE WHEEL STORY

The Impact of Wheels and Tires on Manual Wheelchair Propulsion Efficiency

PRESENTED BY

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Ki Mobility by Etac

1-Maximizing w/c performance, 2- Impact of wheels and tires 3-Optimizing configuration
Up until now, everything has been snippets of science of 'how things work' and what you should know about it as it relates to wc mechanics and propulsion efficiency. Now, we're trying to influence decision making in wheelchair prescription based on that knowledge.

WHY ARE WE TACKLING THIS SUBJECT MATTER?

As individuals involved in prescribing wheelchairs, we need to know and understand that there are factors that can impact the equipment (the WC) and how it performs, and factors that impact the user, as well as the interaction between the two.
Parts one and two of this series will look primarily at the equipment. . .
1-Critically assess the thinking today in the industry/marketplace about what’s important
2-convert that into supporting the NEED for adjustability in wheelchairs
3-Now that we’ve established that wheelchairs can and should be adjusted, we will address how complex all those adjustments can be

The Wheel Story

Imagine…

A ***meticulously*** configured ultralightweight rigid manual wheelchair. . .

So, let’s talk about . . . The Wheel Story

The Wheel Story

Set-up for the user's
- Anatomic measurements
- Postural support needs
- Skill level

So, let's talk about . . . The Wheel Story

The Wheel Story

Aggressive axle position

Stripped down of secondary components

- No anti-tippers
- No armrests
- No wheel locks

The Wheel Story

The end user is expecting a highly efficient, high-performance wheelchair.

The Wheel Story

Now, imagine the chair being issued . . .

The Wheel Story

Now, imagine the chair being issued equipped with mag wheels and pneumatic tires with flat-free inserts.

It may be attributable to human nature – if it's 'worked' in the past, you may be more likely to repeat the process.
Do you actually know that this is not necessarily the most efficient setup, but maybe it's still the right setup for this particular set of circumstances anyway? Or did you just make the choice because it was the no-charge or more expedient thing to do, Did you even include or consult the user in the decision?
(Or. . . It's the most profitable?)

The Wheel Story

Have you made this selection in the past?

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Have you made this selection in the past?

Why did you make that selection?

What influenced that decision?

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The Wheel Story

Have you made this selection in the past?

Why did you make that selection?

What influenced that decision?

- Maintenance considerations
- Environment of use
- User preference
- Previous experience (user, therapist or ATP)

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What Does a Wheelchair User Really Want?

In the world of wheelchair, high performance does not equal the fastest or the most powerful. . . It's the 'fuel' (energy) efficiency that matters
Covered in more detail in the first presentation

What Does a Wheelchair User Really Want?

A wheelchair is a machine
that provides a mechanical advantage
to make mobility easier

In the world of wheelchair, high performance does not equal the fastest or the most powerful. . . It’s the ‘fuel’ (energy) efficiency that matters
Covered in more detail in the first presentation

What Does a Wheelchair User Really Want?

A High-Efficiency Machine

In the world of wheelchair, high performance does not equal the fastest or the most powerful. . . It's the 'fuel' (energy) efficiency that matters
Covered in more detail in the first presentation

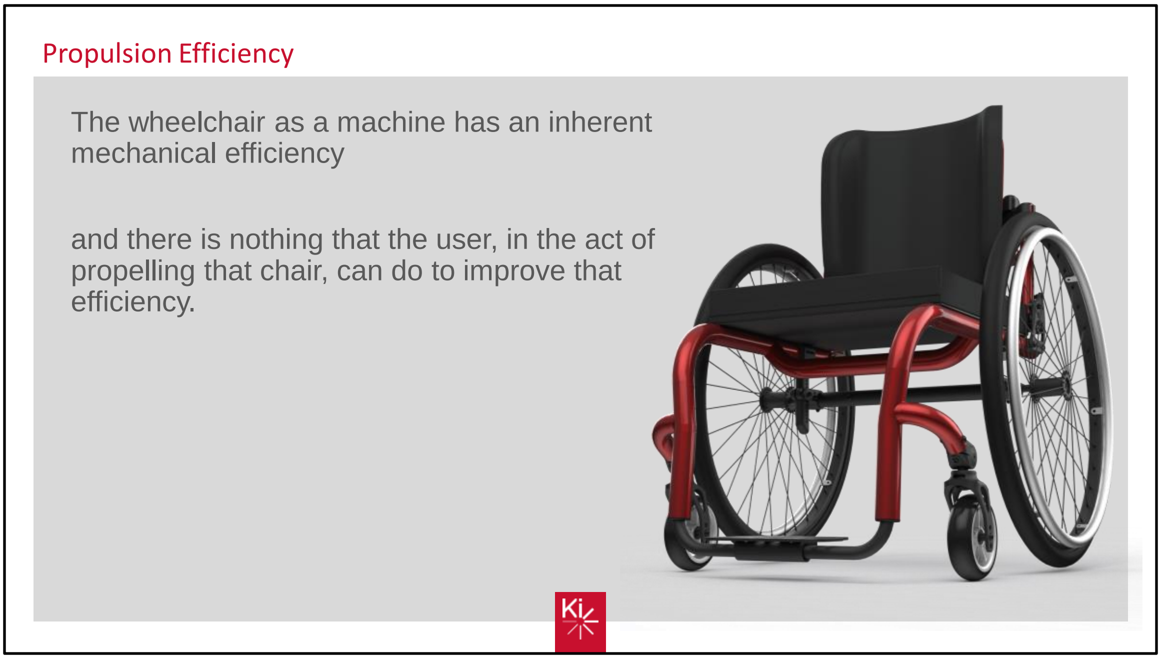
Propulsion Efficiency

HOW DO WE MEASURE EFFICIENCY?

"Work" can be used as measure of efficiency.

The most efficient wheelchair (machine) is the one that takes the ***least*** amount of work to maneuver.

When we talk efficiency, we think of the work it takes to perform a task. . .



What can we do to affect the inherent efficiency of this machine?

Propulsion Efficiency

The wheelchair as a machine has an inherent mechanical efficiency

and there is nothing that the user, **in the act of propelling the chair**, can do to improve that efficiency.

What can we, as professionals, do to affect the inherent efficiency of this machine?

Propulsion Efficiency

What can be done to affect the inherent efficiency of this machine?

- Mass Distribution
  - Wheelbase Adjustment
  - Postural Changes due to Seating Adjustment
- Wheel and Tire selection

Factors that can affect or have been said to predict performance, affect the inherent efficiency. . .
Wheelbase Adjustment and Weight Distribution, achieved by adjusting wheelbase

Propulsion Efficiency

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  - Wheelbase Adjustment
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What can we do to affect the inherent efficiency of this machine?
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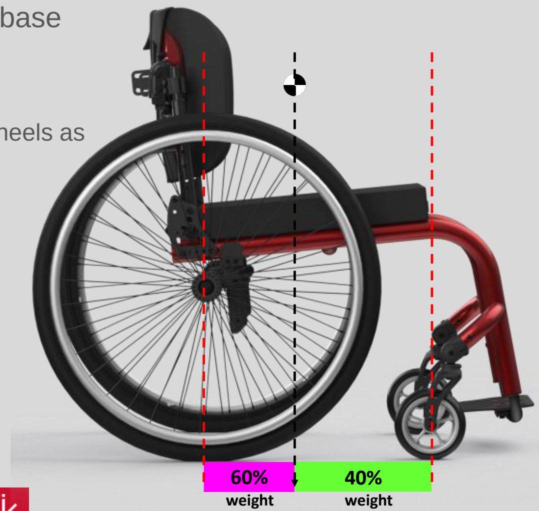
Propulsion Efficiency

Mass Distribution is Impacted by Wheelbase Adjustment

Also known as Center of Gravity (CG)

The proportion of **system** mass over the rear wheels as compared to that over the front wheels

Adjusted by moving rear wheel horizontally,
or caster wheel when possible



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Wheelbase Adjustment and Weight Distribution

Propulsion Efficiency

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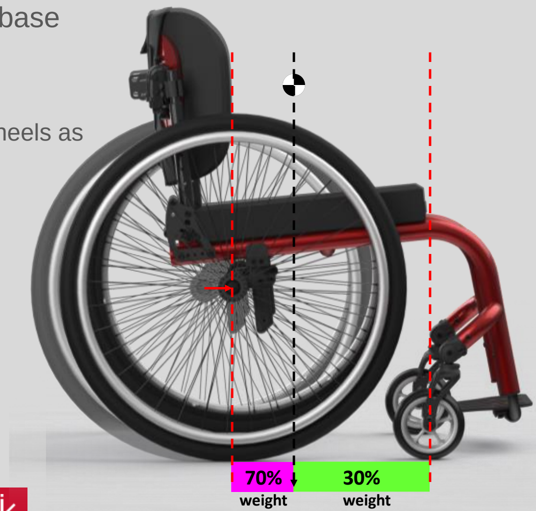
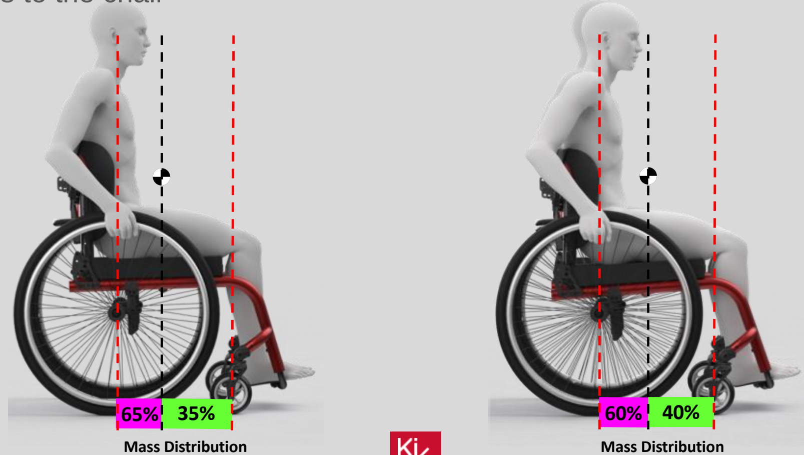


Factors that can affect or have been said to predict performance, affect the inherent efficiency. . .
Wheelbase Adjustment and Weight Distribution

Current research suggests that after weight distribution, wheel and tire selection is critical, which is why we're here in this 2nd episode

Propulsion Efficiency

Mass Distribution can be impacted by changes in posture resulting from changes to the chair

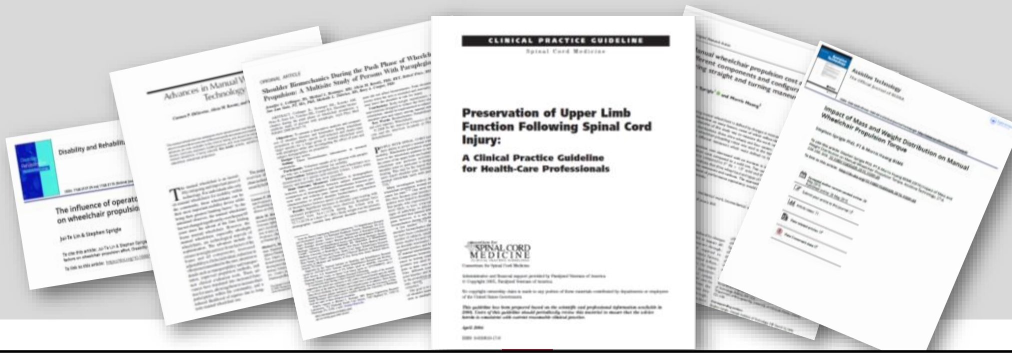


Seating / Postural changes can impact this distribution. Here we see that closing the back angle a few degrees has brought the user's trunk forward, thus shifting their center of mass, and changing the distribution of system weight on the wheelbase. Wheelbase wasn't changed, but where the weight was located on it was.

Rogue 4 hand at 12

Propulsion Efficiency

So, What’s Important?

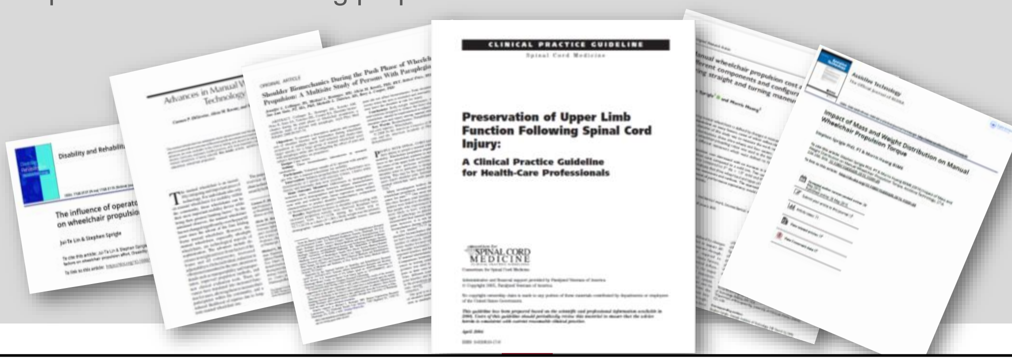


So, What’s Important?
Based on current research there is strong evidence that mass distribution (by means of adjusting wheelbase) is critical to propulsion effort.
The evidence also supports that wheel and tire selection is also a critical factor - so that’s why we’re here.
This quote from Dr. Sprigle highlights what’s really important in terms of affecting propulsion effort (efficiency) (next slide)

Propulsion Efficiency

Dr. Stephen Sprigle, PhD, PT

“When considering propulsion effort within ULW manual wheelchairs, ample scientific evidence suggests that wheels, tires and weight distribution are the most impactful. So, by focusing solely on mass, one neglects the most important factors affecting propulsion effort.“

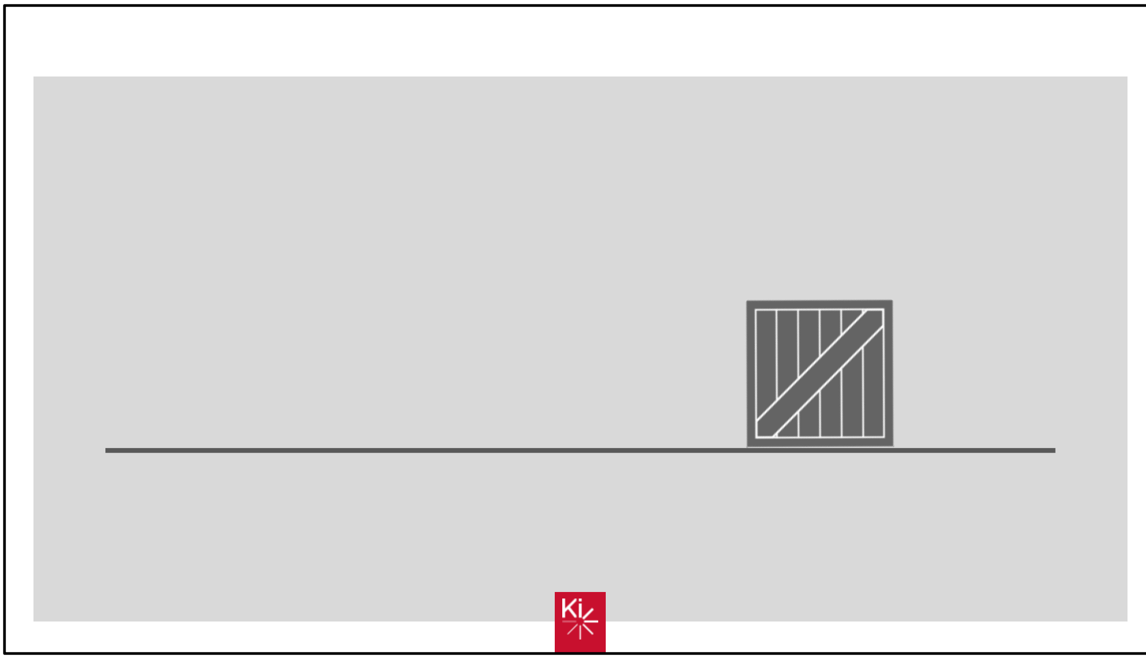


This quote from Dr. Sprigle highlights what’s really important in terms of affecting propulsion effort (efficiency)

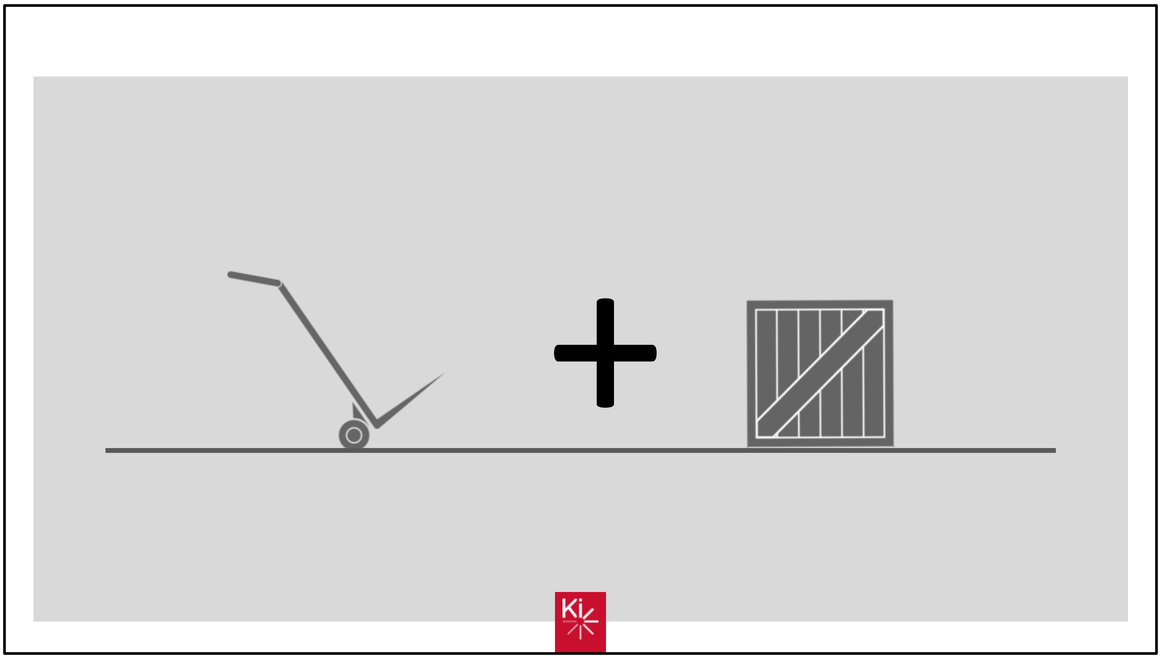
We said this machine makes work easier

But how does it make it easier?

How does a wheel work, what does it actually do?



In short, a dolly making it easier to move a crate
Is equivalent to Wheelchair plus user for easier moving about



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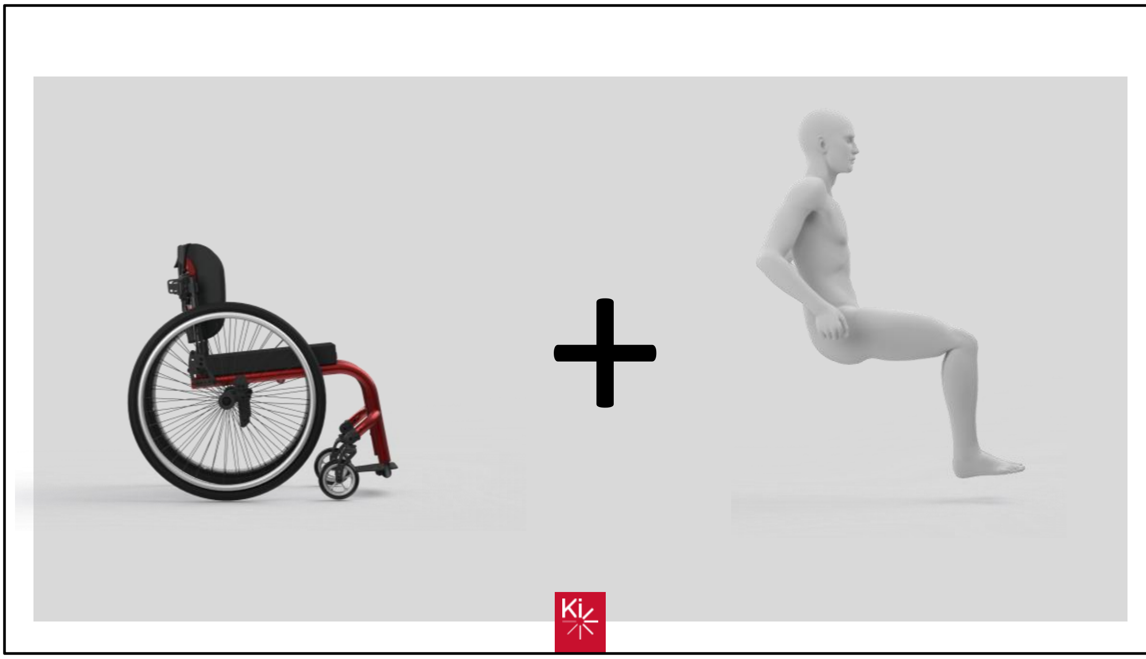
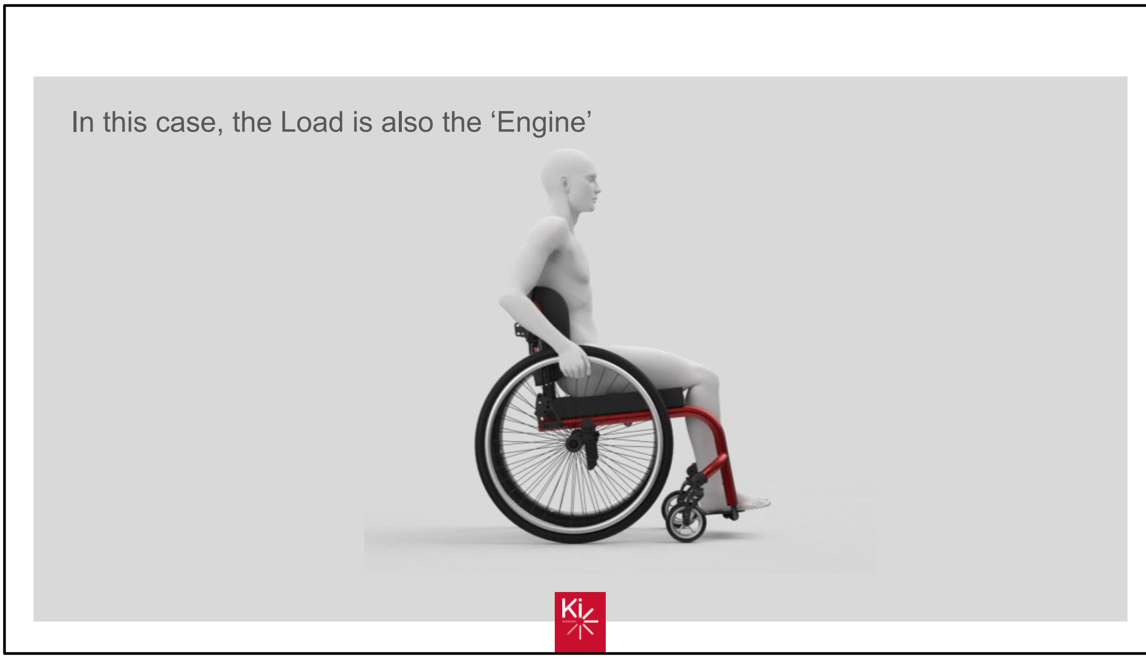


In short, a dolly making it easier to move a crate
Is equivalent to Wheelchair plus user for easier moving about – because of the wheels, of course



A main difference is that the force to move the dolly around is not coming from the occupant.
In a wheelchair, the load is also the engine. . . That must provide the propulsive effort, do the work.

How Do Wheels Work?

How Do Wheels Work?

Wheels Reduce Friction.

Work = Force X Distance

When friction is reduced, the force needed to cover the same distance is less, so work goes down

Remember that crate on the floor? If you try to just push or drag it, you'll encounter a lot of friction.
However, wheels don't eliminate friction entirely. It just means the only appreciable friction to overcome is at the point where the wheel and axle meet—between the relatively smooth inner surface of the wheels and the equally smooth outer surface of the axles around which they turn.

There must be friction between the wheels and the ground or they'd simply slide along (like something being pushed on ice).
The key to how wheels reduce friction is that they can slide more smoothly round their axles than an object can slide across the ground

Friction between each wheel and the ground helps it "dig in" so the wheel can rotate.
Wheeled devices are easier to push because the only real friction you have to work against is between the wheels and their axles. As you push a wheeled device, the relatively smooth inside surfaces of the wheels rotate and slide around the relatively smooth outsides of the axles. The important word here is smooth; the key to how wheels reduce friction is that they can slide more smoothly round their axles than an

object can slide across the ground

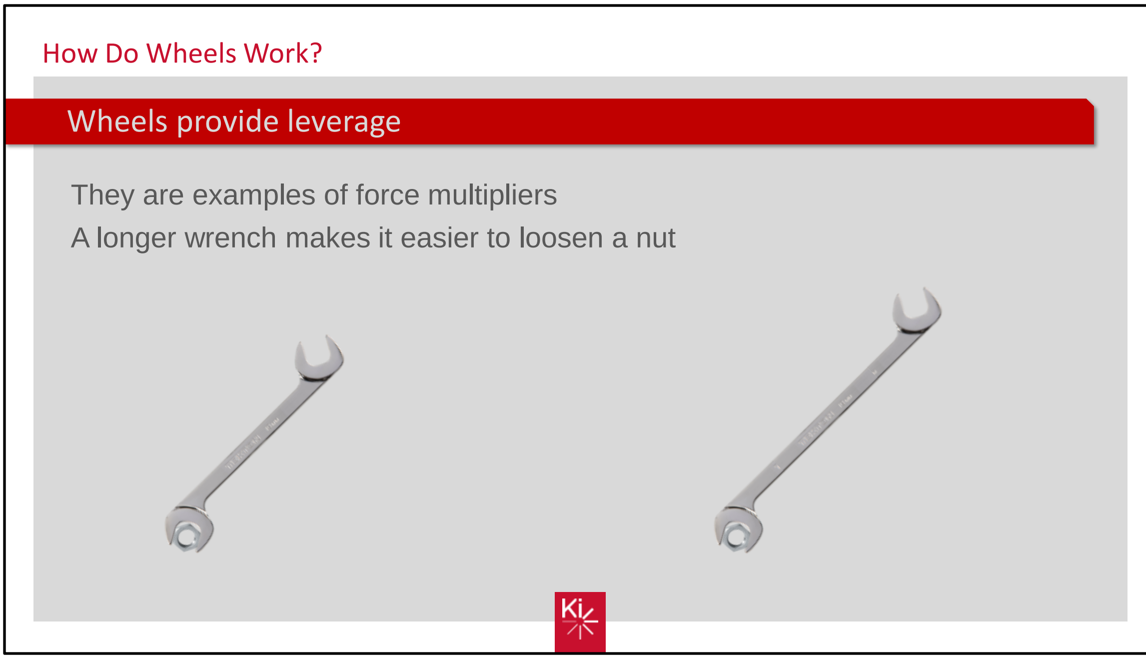
How Do Wheels Work?

Wheels provide leverage

They are examples of force multipliers

A wheelchair with bigger wheels is easier to push because its larger-diameter wheels work like longer levers, multiplying the pushing or pulling force and making it easier to turn the wheels around their axles—

The rim of a wheel turns a greater distance than the axle so, in the case where you're pushing a device from behind or pulling it from the front, there is more force at the axle than at the rim.
it really helps if your device has big wheels because they give you more leverage, magnify your pushing force, and help you overcome the force of friction at the axles.



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How Do Wheels Work?

Wheels provide leverage

Wheels are also force multipliers

- Larger diameter wheels provide greater leverage
- Making it easier to rotate the wheel same degrees

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How Do Wheels Work?

Turn a wheel at the rim and the force you apply is multiplied to produce a bigger force at the axle.

The bigger the wheel, the longer the lever, and the greater the effect.

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How Do Wheels Work?

Turn the wheel at the center instead (like on a bicycle), and it works the opposite way.

Now the rim of the wheel goes further and faster, but it takes more force to turn it.

That's how you can use a bigger wheel to multiply speed.

However, if you apply a force at the center of a wheel, the leverage works in reverse and you get less force at the rim, even though you're getting more speed there. Just as with gears, like on a bicycle, you can't increase both the force and the speed at the same time. If you increase one of them, you must reduce the other, otherwise you'd be using a wheel to make energy out of thin air (which violates a basic law of physics called the conservation of energy).

How Do Wheels Work?

This is why some sport chairs will use a smaller diameter handrim when speed is important

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How Do Wheels Work?

Or, when trying to negotiate an incline, some people may grasp the larger diameter tire instead of the handrim.

An instance when extra leverage (force) is needed

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Rolling Efficiency

Rolling Efficiency

When a wheel rolls on a surface, Energy is Lost

This is typically referred to as Rolling Resistance

The lower the Rolling Resistance the more Efficient it is

The energy needed to deform (a tire/wheel) is greater than the energy recovered when the deforming force is removed – this is a factor of rolling resistance.

There are numerous studies that discuss that rolling resistance is affected by wheel/tire characteristics

Rolling Efficiency

Energy Loss Parameters include:

1-Rebound Loss

2-Deformation

3-Slippage

Rebound losses in the technical literature will be referred to as hysteresis

Rolling resistance, sometimes called rolling friction or rolling drag, is the force resisting the motion when a body (such as a ball, tire, or wheel) rolls on a surface. It is mainly caused by non-elastic effects; that is, not all the energy needed for deformation (or movement) of the wheel, roadbed, etc., is recovered when the pressure is removed. Two forms of this are hysteresis losses (see below), and permanent (plastic) deformation of the object or the surface (e.g. soil). Another cause of rolling resistance lies in the slippage between the wheel and the surface, which dissipates energy. Note that only the last of these effects involves friction, therefore the name "rolling friction" is to an extent a

Rolling Efficiency

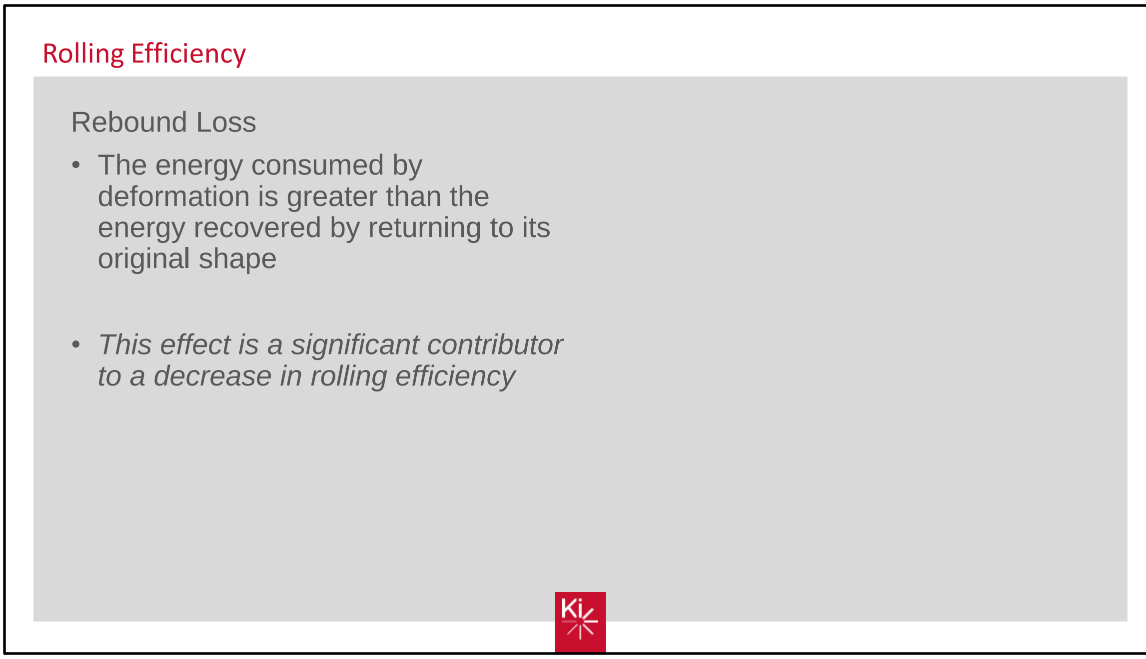
Elasticity

- The ability of an object or material to resume its original shape after being deformed

Before we talk about rebound loss, let's define rebound, or elasticity
Define viscoelastic, and elastic
Hysteresis: A characteristic of a deformable material such that the energy of deformation is greater than the energy of recovery. The rubber compound in a tire exhibits hysteresis. As the tire rotates under the weight of the vehicle, it experiences repeated cycles of deformation and recovery, and it dissipates the hysteresis energy loss as heat. Hysteresis is the main cause of energy loss associated with rolling resistance and is attributed to the viscoelastic characteristics of the rubber.
The losses due to hysteresis also depend strongly on the material properties of the wheel or tire and the surface. For example, a rubber tire will have higher rolling resistance on a paved road than a steel railroad wheel on a steel rail.

SuperBalls are claimed to have a resilience of about 90 percent. That means if you drop a SuperBall from 12 inches (30.48 centimeters) onto a hard surface, it will bounce back to about 10.8 inches (27.43 centimeters), then 9.72 inches (24.69 centimeters), then 8.75 inches

(22.23 centimeters) and so on. Why doesn't it bounce back to 100 percent of its previous height? Like all **elastic materials**, SuperBalls easily regain their shape after being distorted. But some of the energy that goes into distorting the ball is lost as heat. In other words, a little bit of energy is lost on each bounce.



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Rolling Efficiency

Rebound Loss

- Attributed to the elastic characteristics of the tire material

Many of us of a certain age may remember the Super Ball. . .

SuperBalls are claimed to have a resilience of about 90 percent. Like all **elastic materials**, SuperBalls easily regain their shape after being distorted. But some of the energy that goes into distorting the ball is lost as heat. In other words, a little bit of energy is lost on each bounce.

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Rolling Efficiency

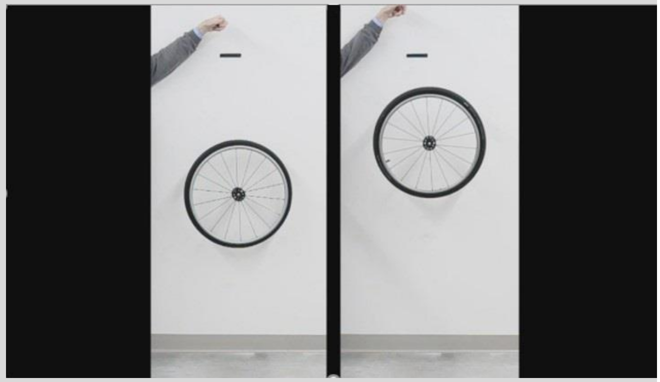
Rebound Loss

- Comparison of two wheels

We set up a drop test, like dropping a ball, and letting it bounce back up, rebound. This drop comparison is of a solid polyurethane tire (left) vs a high pressure pneumatic (right). The video stops at the high point of the rebound of each.
Left: Schwalbe Sentinel Solid vs right: Schwalbe Marathon

Rolling Efficiency

So, one rebounded more efficiently, but does that actually affect rolling efficiency?

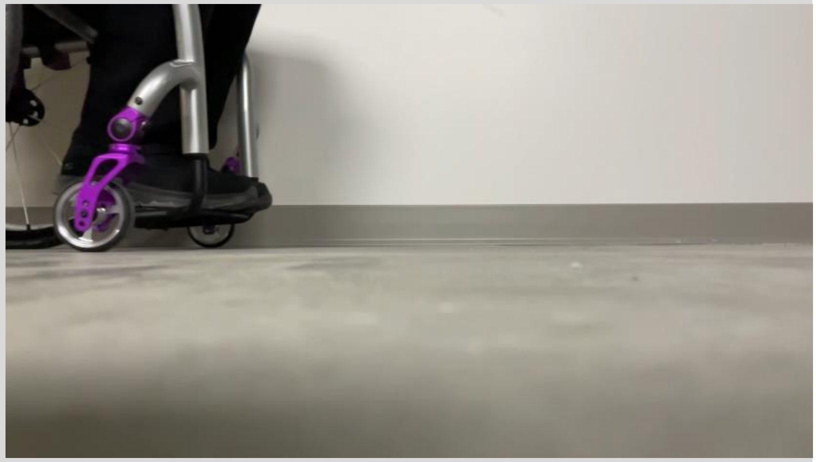


Still shot of last frame of video – Does it affect rolling efficiency?

Rolling Efficiency

Deformation

- Of the Tire



As the tire rotates under the weight of the load, it experiences repeated cycles of deformation and recovery, and it dissipates the Rebound (hysteresis) energy loss as heat. Rebound loss is the main cause of energy loss associated with rolling resistance and is attributed to the viscoelastic characteristics of the rubber.
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Rolling Efficiency

Deformation

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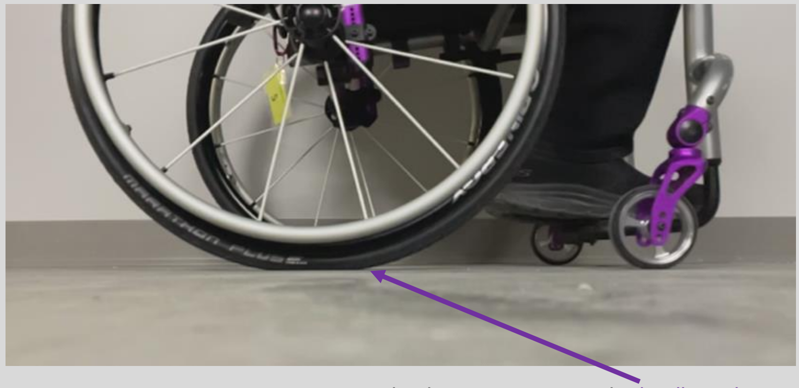

The tire compresses at the leading edge, consuming energy.

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Rolling Efficiency

Deformation

- Of the Tire

A more efficient wheel returns that energy at the trailing edge with less rebound loss, and is therefore more efficient in the process

The tire compresses at the leading edge, consuming energy.

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Rolling Efficiency

Deformation

- Of the Rolling Surface
    - May rebound as well

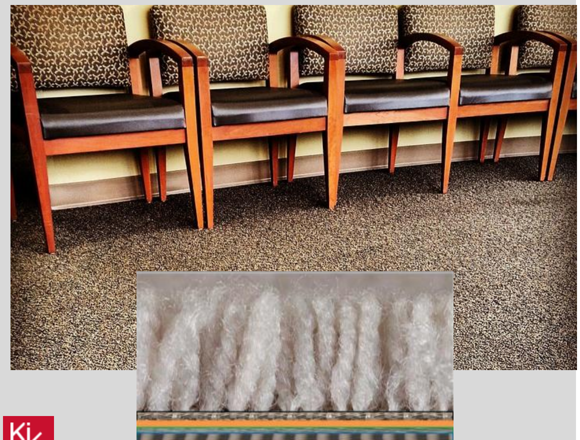
Deformation of the tire, and the lost energy associated with it is a factor, but we can also have deformation of the rolling surface as well.
Some surfaces are actually designed with some rebound (energy return) built in, but many of them will permanently deform (see next couple slides)

Rolling Efficiency

Deformation

- Of the Rolling Surface

  (such as carpet, sand, gravel or soft dirt)
  - May be permanent



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Rolling Efficiency

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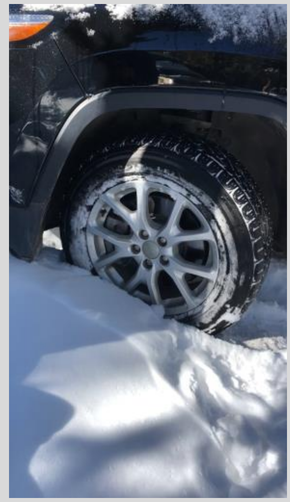
Deformation of the tire, and the lost energy associated with it is a factor, but we can also have deformation of the rolling surface as well.
Some surfaces are actually designed with some rebound (energy return) built in, but many of them will permanently deform – like this carpet, or this sand. . .

Rolling Efficiency

Slippage

- Between the wheel and the surface
  - Which dissipates energy



Another contributor to decreased of rolling efficiency is when there is not enough traction (coefficient of friction) and there is slippage between the wheel and the rolling surface, which dissipates energy.

Rolling Efficiency

Other factors contributing to Rolling Efficiency:

Tire Design

- Material
- Profile
- Construction

Contact Patch

Inflation pressure

Wheel Diameter

Rolling Efficiency

Tire Design

Material

Tires are made with Rubber, or Poly

We tend to know tires are made with rubber, and we see choices on order forms that mention poly, but what is it?

Tire Design

Material

What the heck is poly?

Rolling Efficiency

Tire Design

Material

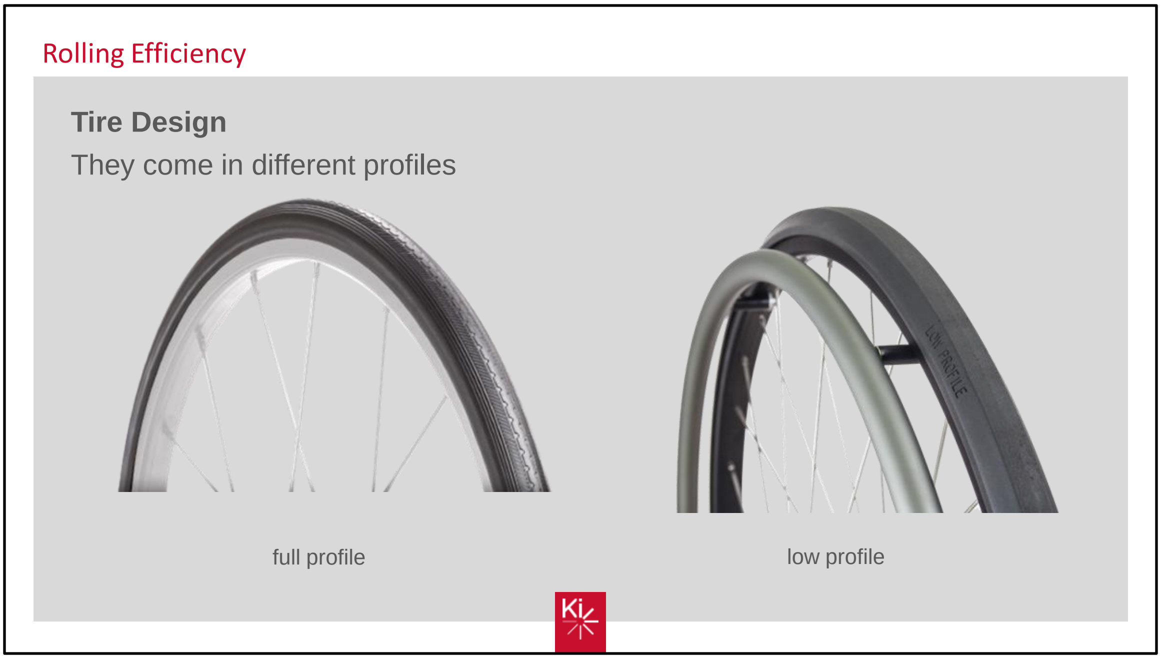
Poly comes from the word Polyurethane

Polyurethane is a synthetic ‘rubber’ like material commonly used in the manufacture of tires

It is formulated in different levels of softness or hardness (durometer)

Poly is common in warehouse settings for example, as it is non marking, and has other benefits:

Higher load capacity, wear and abrasion resistance (4x rubber), chemical resistance and a few others that may not matter to wc users.



We can see it in a different profiles
Poly is common in warehouse settings for example, as it is non marking, and has other benefits:
Higher load capacity, wear and abrasion resistance (4x rubber), chemical resistance and a few others that may be mostly irrelevant to wc users.
Rubber may be used for tires as well, but not common for solid tires – many air filled tires are rubber though

Rolling Efficiency

Tire Design

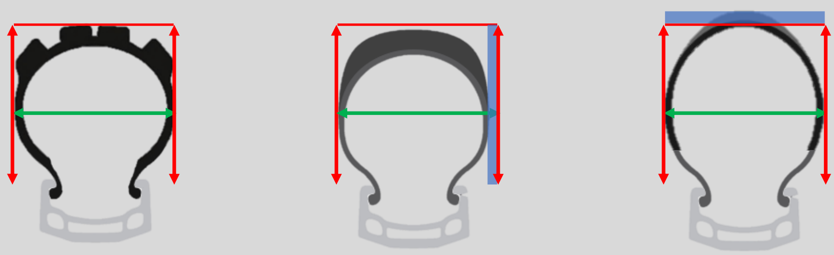
Profile

Now, what the heck is profile?

Rolling Efficiency

Tire Design

Profile

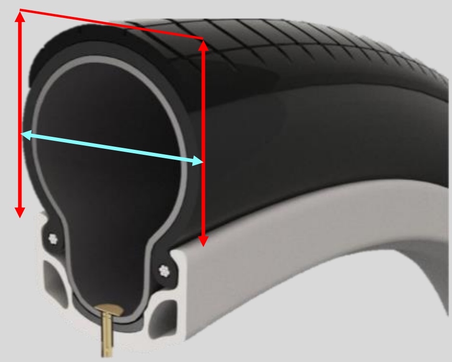


Profile is all the characteristics of the 'shape' of the tire, cross sectionally – how wide, how tall, how round, tread type etc.

Rolling Efficiency

Tire Design

Profile



stated tire width, as a specification, may not be equal to ‘functional’ tire width

People may purchase a tire based on width, but an understanding of Profile or Shape is important.

Point out that spec stated tire width, on a sidewall or an order form, may not equal ‘functional’ tire width in contact with the ground, due to profile, so even though we may refer to width, we’re really talking about the functional width, or an aspect of what’s called the “contact patch”

Rolling Efficiency

Tire Design

Tire Type

Pneumatic / Air-Filled

Classic rubber tire, with a rubber inner tube. Pumped up with air through a valve stem (shown at bottom of cut-away). Requires maintenance.

Rolling Efficiency

Tire Design

Tire Type

Two types of solid tires:

- Airless Insert

- Often selected because it is considered to be maintenance free

Many mfrs have the option to select a pneumatic tire with airless insert.

- Instead of being air filled, it has a low-density foam insert inside the tire where the air would normally be

Airless insert aka solid insert aka airless insert, aka flat free.

It is a solid insert. It does not contain air that can leak out, so it can't go flat.

But, is a solid tire, or a pneumatic with solid insert a good choice. . . ?

Rolling Efficiency

Tire Design

Tire Type

Two types of solid tires:

- Fully Solid tire

- Often selected because it is considered to be maintenance free

This is just a fully solid tire. Like the flat free insert, it does not contain air that can leak out, so it can’t go flat.
But, is a solid tire, or a pneumatic with solid insert a good choice. . . ?

Rolling Efficiency

Tire Design

Tire Type – Rebound Loss

Recognize that each of these tire types is going to behave differently with regard to rebound loss, but the pneumatic is the **ONLY** one that can be adjusted for it

Rolling Efficiency

Tire Design

Tire Type

Pneumatic tires exhibited lower rolling resistance than solid tires

Sawatsky, et al, 2004

As load increased, solid tires experienced larger increases in rolling resistance than pneumatic tires.

Kwarciak, et al, 2004


JRRD

Journal of Rehabilitation Research & Development

Evaluation of wheelchair tire rolling resistance using dynamometer-based coast-down tests

The research consistently shows that Pneumatics have better rolling efficiency than solid tires. In fact, in the Sawatsky study, they noted that even when the air-filled tires were underinflated to 25% of recommended inflation pressure, they still outperformed the solid options.

In another study by Kwarciak and colleagues, they observed that the energy sucking effect of solid tires is more pronounced at heavier loads

Rolling Efficiency

Tire Design

Now, what the heck is contact patch?

As I said, the specified tire width may not be equal to the 'functional' width – That's contact patch

Rolling Efficiency

Tire Design

Contact Patch

Deformed area in contact with the support surface

Includes:

- Surface area (length x width)
- Shape (how long, or how wide)

Surface area is just that – how many square centimeters, inches, etc.
Shape is “what does it look like?”, long and skinny, short and wide, etc.
Contact patch can be related to tire width, but remember, profile does not necessarily equal width

Rolling Efficiency

Contact Patch is a function of Pressure and Load

Pressure = Load / Area

PSI = Pounds / Square Inch

Can prove with simple equation of pressure

Pressure = force/area (force [e.g., system weight] will remain constant)

Pressure of 2psi: 4# / 2 in^2 = 2psi (2psi = 4#/2 in^2)

Increase pressure to 4psi: 4# / 4 in^2 = 1psi

Off road it is exactly the reverse: The lower the inflation pressure, the lower the rolling resistance. This applies equally on hard gravel roads and soft forest tracks.

Explanation: A tire with low inflation pressure can adapt better to a rugged surface. It sinks into the ground less and the whole rotational mass is held back much less by the uneven surface.

Generally, smooth treads roll better than coarse treads. Tall lugs and wide gaps usually have a detrimental effect on rolling resistance.

Rolling Efficiency

Contact Patch is a function of Pressure and Load

Pressure = Load / Area

Tire Pressure in PSI = System Weight in Pounds / Area in Square Inches

(in a given setup, load [e.g., system weight] will remain constant)

Can prove with simple equation of pressure
Pressure = force/area (force [e.g., system weight] will remain constant)
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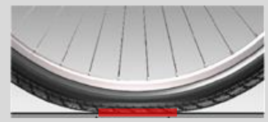
Rolling Efficiency

Inflation Pressure (PSI)

We showed, Tires deform under load.



On a completely smooth surface the following applies:

The higher the inflation pressure,
The less the tire deformation (smaller the contact patch)
Thus, less rolling resistance.

Schwalbetires.com

For a given wheel and tire combo, and a given load, this is true.
Off road it is exactly the reverse: The lower the inflation pressure, the lower the rolling resistance. This applies equally on hard gravel roads and soft forest tracks. Explanation: A tire with low inflation pressure can adapt better to a rugged surface. It sinks into the ground less and the whole rotational mass is held back much less by the uneven surface.

Generally, smooth treads roll better than coarse treads. Tall lugs and wide gaps usually have a detrimental effect on rolling resistance.

Rolling Efficiency

Contact Patch

A Wider Tire (contact patch) rolls better than a narrower one.

Skeptical?

At the same pressure, a Narrower Tire (contact patch) deforms more.

Schwalbetires.com

The statement has a qualifier: "at the same pressure"
Wide patch may be thought of as tire width, but due to profile differences, that's not necessarily the case. Pressure = force per unit of area
P = F/a
F/P = a
Tire pressure in psi = body (system) weight / area
Off road it is exactly the reverse: The lower the inflation pressure, the lower the rolling resistance. This applies equally on hard gravel roads and soft forest tracks. Explanation: A tire with low inflation pressure can adapt better to a rugged surface. It sinks into the ground less and the whole rotational mass is held back much less by the uneven surface.

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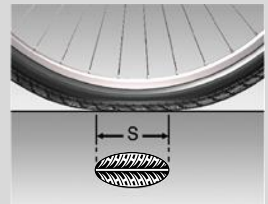
Rolling Efficiency

We said Tires Deform Under Load



The contact patch is the surface area in contact with the ground.

Pressure = force per unit of area. If force (system weight) is constant, and pressure is constant, then area must remain constant, and in a wider tire patch that means the length is less

Area = width x length (e.g. 4 x 6 = 24), or Area= 2xwidth x 1/2 length (e.g. 8 x 3 = 24)

P = F/a

F/P = a

Rolling Efficiency

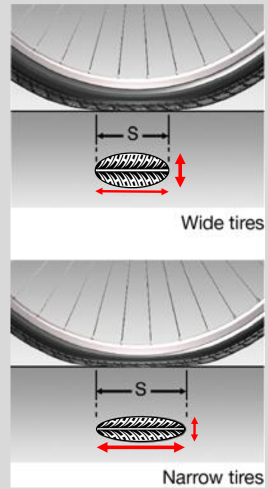
We said Tires Deform Under Load

At the same inflation pressure, a wide tire and a narrow tire have the same **amount** of contact area,

But it's **not the same shape.**

A wide tire is flattened over its width, whereas a narrow tire has a slimmer but longer contact area.

Schwalbetires.com



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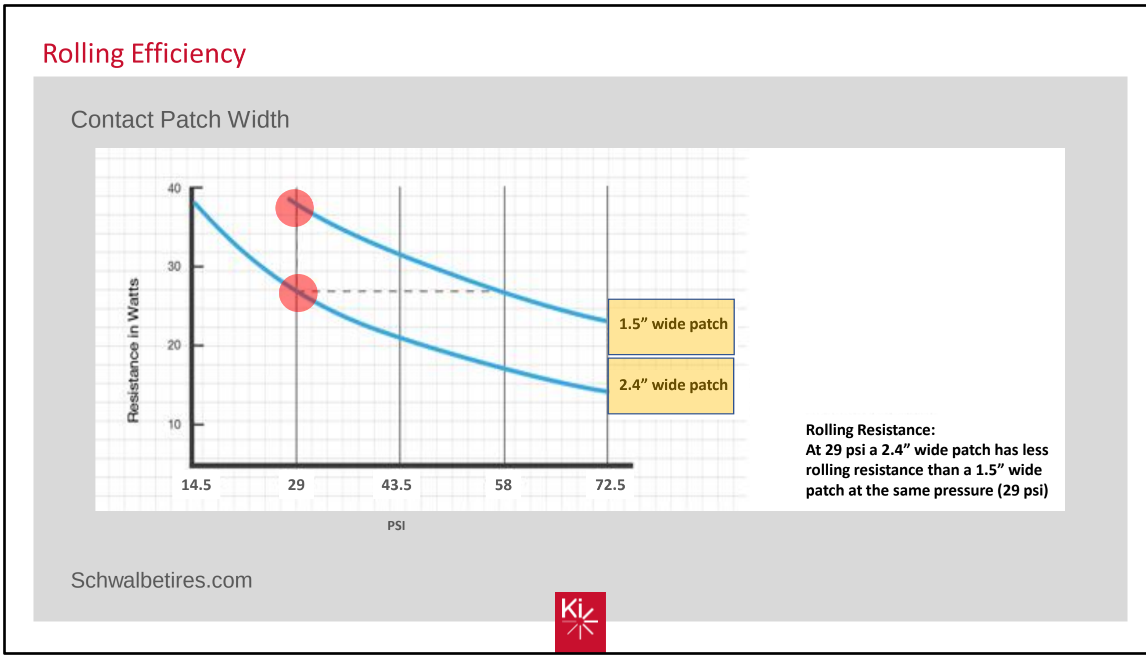

We see both tires at the same pressure, 29 psi in this example, but the narrower tire, the top one, has higher resistance than the wider one. However, when we increase the pressure in the narrower tire, then we can see that the resistance at 58 psi for the narrow is equal to the resistance for the wider at the lower pressure of 29 psi. We'll talk more about wide vs narrow in a couple slides.

Rolling Efficiency

But I’ve always heard that narrow tires are better. . .

They can be. . .

A Wider Tire (contact patch) only rolls more efficiently with the **<u>same</u>** inflation pressure.

The advantage of a Narrower Tire (contact patch) is that they are used with a higher inflation pressure.

Let’s look at that graph again. . .

Can prove with simple equation of pressure
Pressure = force/area (force [e.g., system weight] will remain constant)
Pressure of 2psi: 4# / 2 in^2 = 2psi (2psi = 4#/2 in^2)
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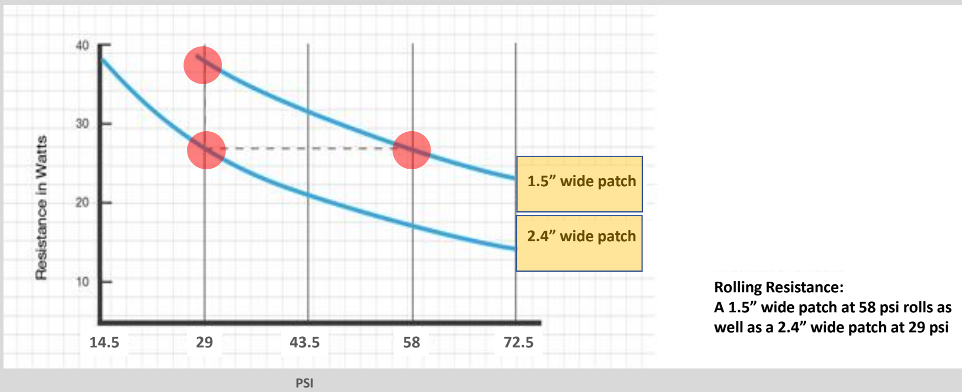
Off road it is exactly the reverse: The lower the inflation pressure, the lower the rolling resistance. This applies equally on hard gravel roads and soft forest tracks.
Explanation: A tire with low inflation pressure can adapt better to a rugged surface. It sinks into the ground less and the whole rotational mass is held back much less by the uneven surface.

Generally, smooth treads roll better than coarse treads. Tall lugs and wide gaps usually have a detrimental effect on rolling resistance.

Rolling Efficiency

Contact Patch Width



Schwalbetires.com

We see both tires at the same pressure, 29 psi in this example, but the narrower tire, the top one, has higher resistance than the wider one. However, when we increase the pressure in the narrower tire, then we can see that the resistance at 58 psi for the narrow is equal to the resistance for the wider at the lower pressure of 29 psi. We'll talk more about wide vs narrow in a couple slides.

Rolling Efficiency

Now, at a higher pressure,

- The Narrower Tire deforms less
- Has less **Area** in the contact patch 
- Has better rolling efficiency due to less deformation

Can prove with simple equation of pressure
Pressure = force/area (force [e.g., system weight] will remain constant)
Pressure of 2psi: 4# / 2 in^2 = 2psi (2psi = 4#/2 in^2)
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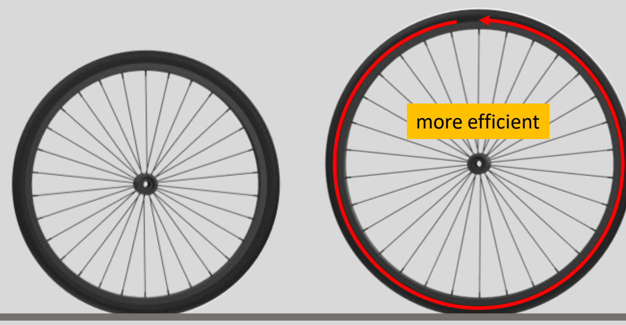
Rolling Efficiency

Tires with a Larger Circumference ($C = \pi\ x\ Diameter$) have a higher rolling efficiency than those with a Smaller Circumference.

Schwalbetires.com



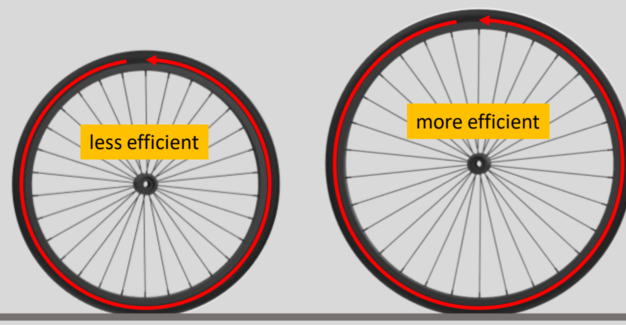
Will just make the statement, but not take the time to try to provide the explanation.

The contact patch is related to the circumference, and with a smaller diameter wheel at the same width and pressure, the flattened portion of the circumference represents a greater portion of that circumference, because tire deformation is proportionally greater.
Given a 4” long contact patch, that represents 6.5% of the 20” wheel’s circumference, and 5.3% of the 24” wheel’s
It’s the same principle we discussed with the longer and narrower contact patch

Rolling Efficiency

Tires with a Larger Circumference ($C = \pi \ x \ Diameter$) have a higher rolling efficiency than those with a Smaller Circumference.

Schwalbetires.com



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The contact patch is related to the circumference, and with a smaller diameter wheel at the same width and pressure, the flattened portion of the circumference represents a greater portion of that circumference, because tire deformation is proportionally greater.
Given a 4” long contact patch, that represents 6.5% of the 20” wheel’s circumference, and 5.3% of the 24” wheel’s
It’s the same principle we discussed 6 slides ago with the longer and narrower contact patch

Rolling Efficiency

Kauzlarich and Thacker determined that, given the same load and same wheel material, rolling resistance is inversely proportional to wheel diameter.

(Kauzlarich and Thacker, 1985)

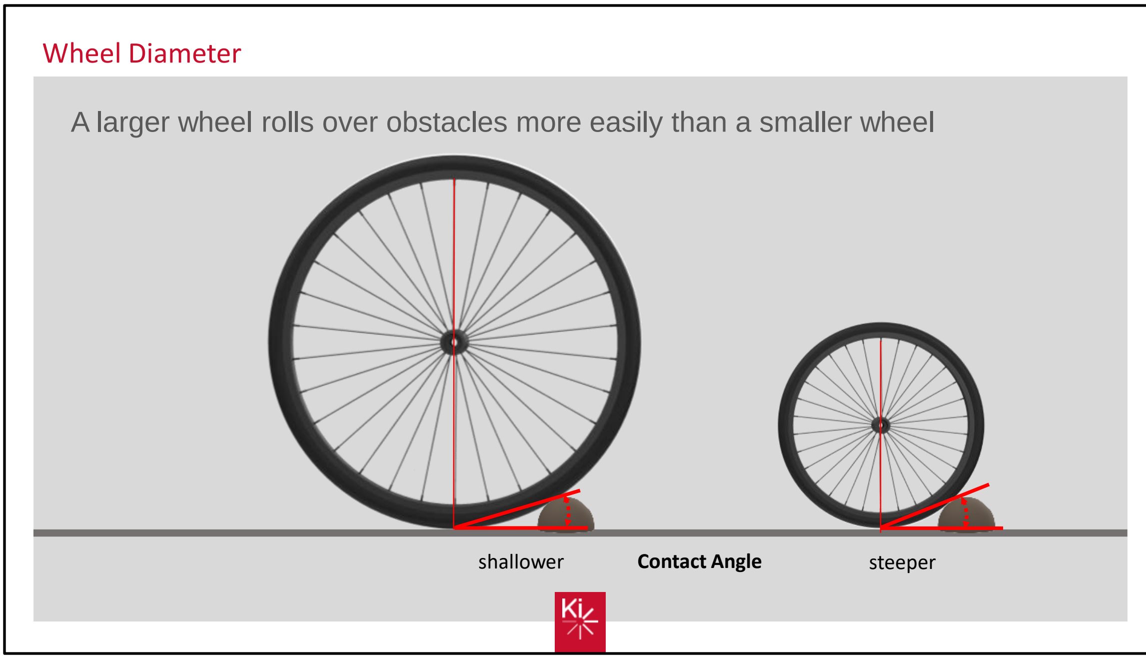

Veterans Administration

Wheelchair tire rolling resistance and fatigue

JAMES J. KAUZLARICH, PH.D.; JOHN G. THACKER, PH.D.

RR is inversely related to radius

Kauzlarich and Thacker determined that, given the same load and same wheel material, rolling resistance is inversely proportional to wheel radius

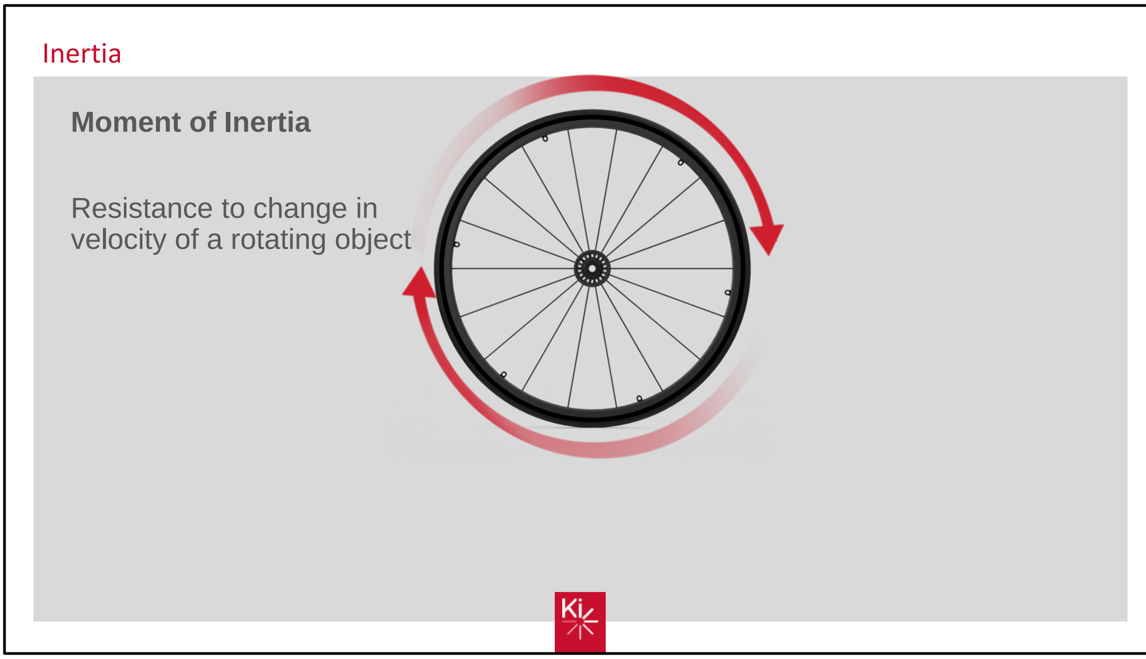


A larger wheel rolls over obstacles more easily than a smaller wheel. An extreme example is how a small obstacle can stop a caster wheel (even like on a grocery cart), but a large rear wheel rolls right over it without even much of a 'bump'
Obstacles could be an upward protrusion such as a threshold, or it could be a downward one, such as a seam in concrete.
When a wheel makes contact with a square-edge obstacle, the contact angle = the angle of the tangent of the wheel at point of contact with the square edge obstacle and the horizontal as shown above.
https://www.evo.com/guides/mountain-bike-wheel-size

Inertia

Inertia

Axis of Rotation



When we are talking about rotating mass, we’re talking not just about the tire we’ve been discussing, but the wheel it goes on.
Moment of inertia is resistance to change in angular velocity about an axis of rotation.

Inertia

Moment of Inertia

Related to both Radius and Mass.

Moment of Inertia (I)

= Mass x $Radius^2$

A wheel with more mass will have a higher moment of inertia than one with less mass

It’s not just how much mass is there, but WHERE is it located on the wheel

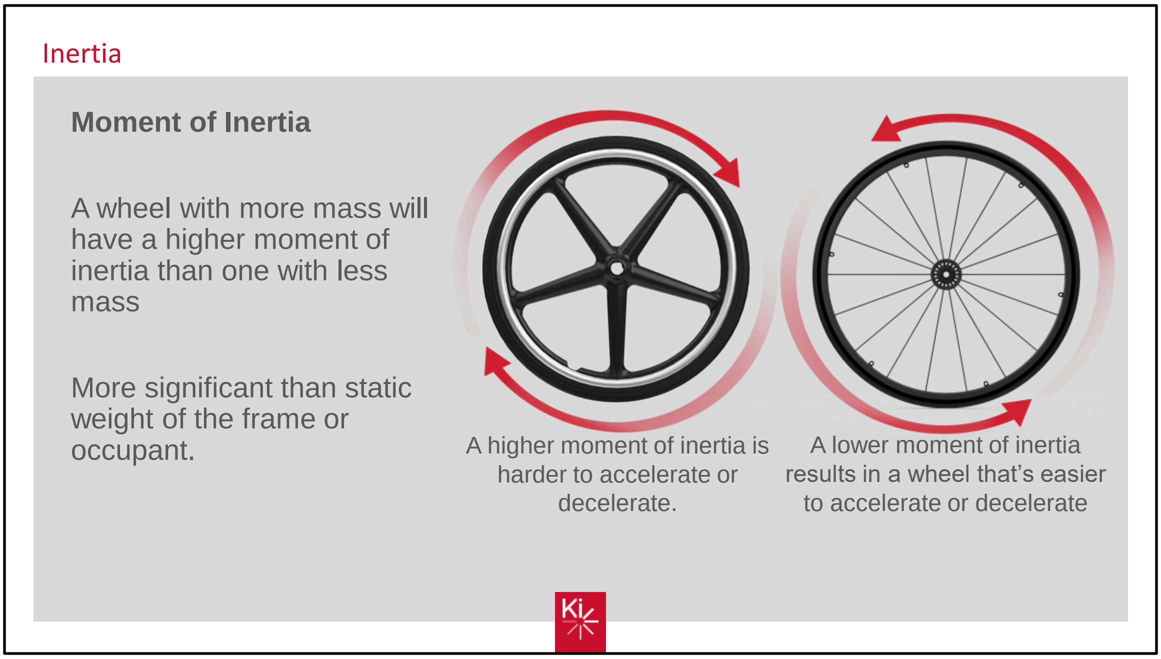
Inertia

Moment of Inertia

A wheel with more mass will have a higher moment of inertia than one with less mass

A higher moment of inertia is harder to accelerate or decelerate.

When we are talking about rotating mass, we're talking not just about the tire we've been discussing, but the wheel it goes on.
Moment of inertia is resistance to change in angular velocity about an axis of rotation.
Permobil video of rotational video of two wheels side by side?



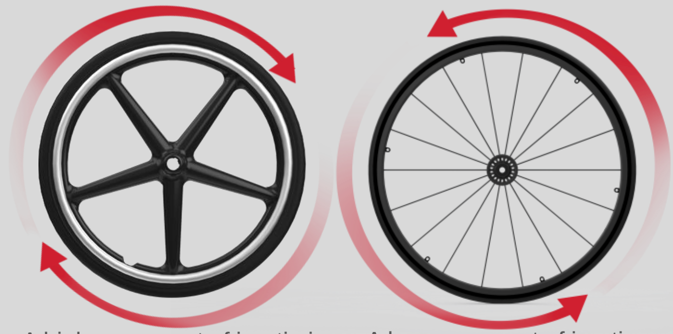
For rectilinear, straightforward movement, mass on the frame doesn't matter as much as rotating mass on the wheels

Inertia

Moment of Inertia

A wheel with more mass will have a higher moment of inertia than one with less mass

More significant than static weight of the frame or occupant.



A higher moment of inertia is harder to accelerate or decelerate.

A lower moment of inertia results in a wheel that's easier to accelerate or decelerate

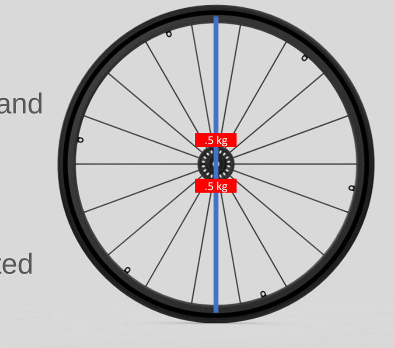
Important consideration in tires, but maybe more important in wheels (mag vs spoke)

For rectilinear, straightforward movement, mass on the frame doesn't matter as much as rotating mass on the wheels

Inertia

Moment of Inertia

Related to both Radius and Mass.



Where the mass is located matters

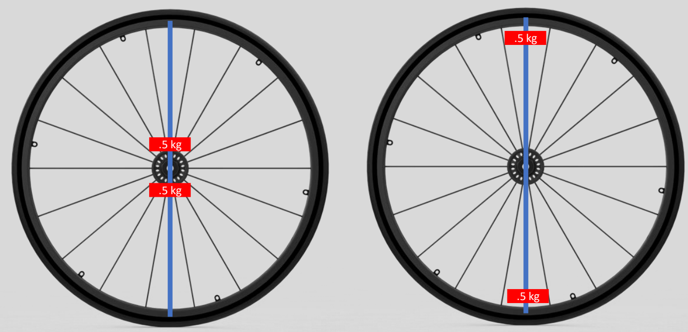
It’s not just how much mass is there, but WHERE is it located on the wheel
Remember, the value of the radius is multiplied times itself, so mass close to center of rotation (CoR) will be multiplied by a much lower value, than the same mass at a farther distance from the CoR

Inertia

Moment of Inertia

Related to both Radius and Mass.

Where the mass is located matters



It’s not just how much mass is there, but WHERE is it located on the wheel
Remember, the value of the radius is multiplied times itself, so mass close to center of rotation (CoR) will be multiplied by a much lower value, than the same mass at a farther distance from the CoR

Inertia

Where the mass is located matters

Inertia

How much mass matters

Inertia

Why Does Rotating Mass Matter?

Manual Wheelchair Use:
Bouts of Mobility in Everyday Life

Sonenblum and Sprigle, 2012

Inertia

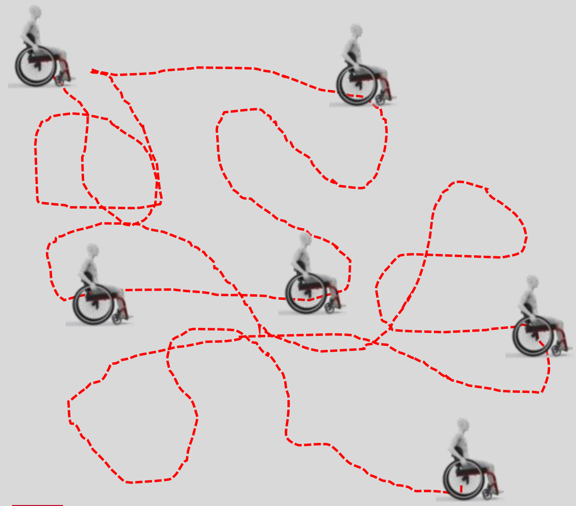
Manual Wheelchair Use:
Bouts of Mobility Study

Results:
Mean Daily Use

1.95 km (~1.2mi)
58 min/day (10% time up)
96 bouts

Lots of starts, stops and turns

Sonenblum, Sprigle and Lopez, 2012



In the context of daily wc use, many bouts of mobility are lots of starts, stops and turns – not too many instances of picking up speed and needing to keep it for distance

Inertia

Dealing with Moment of Inertia in another Axis of Rotation

Inertia

Dealing with Moment of Inertia in another Axis of Rotation (Yaw)

“rogue 5 – unoccupied” is left image
“catalyst 1 – front no camber” is right image

Inertia

Yaw Inertia

Turn your shopping cart at the end of the aisle – would you rather have the case of water out at the end of the cart, or close to you, over the rear wheels?

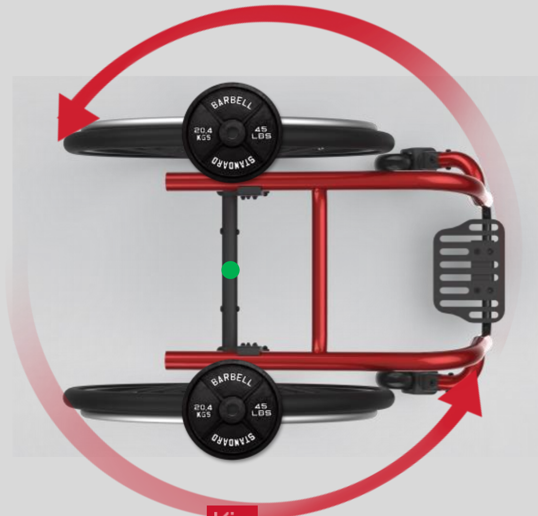
Inertia

Yaw Inertia

Turn your shopping cart at the end of the aisle – would you rather have the case of water out at the end of the cart, or close to you, over the rear wheels?

Inertia

Yaw Inertia



Wheel Construction

Wheel Construction

Mag Wheels – functionally a solid 'disc'

- with sections 'removed'
- Support columns are 'spokes', but not in the sense of wire spokes under tension
- Weight is being 'held up' from underneath

Wheel Construction

Spoke wheels

Hold their form by means of tension on the spokes

- Weight is being 'suspended' from above

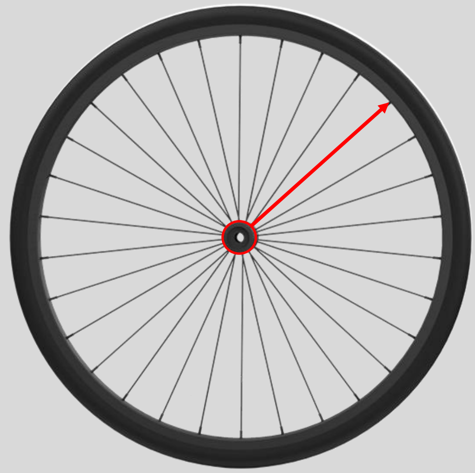
What matters?

- how the spokes are oriented
- how thick/strong they are
- length

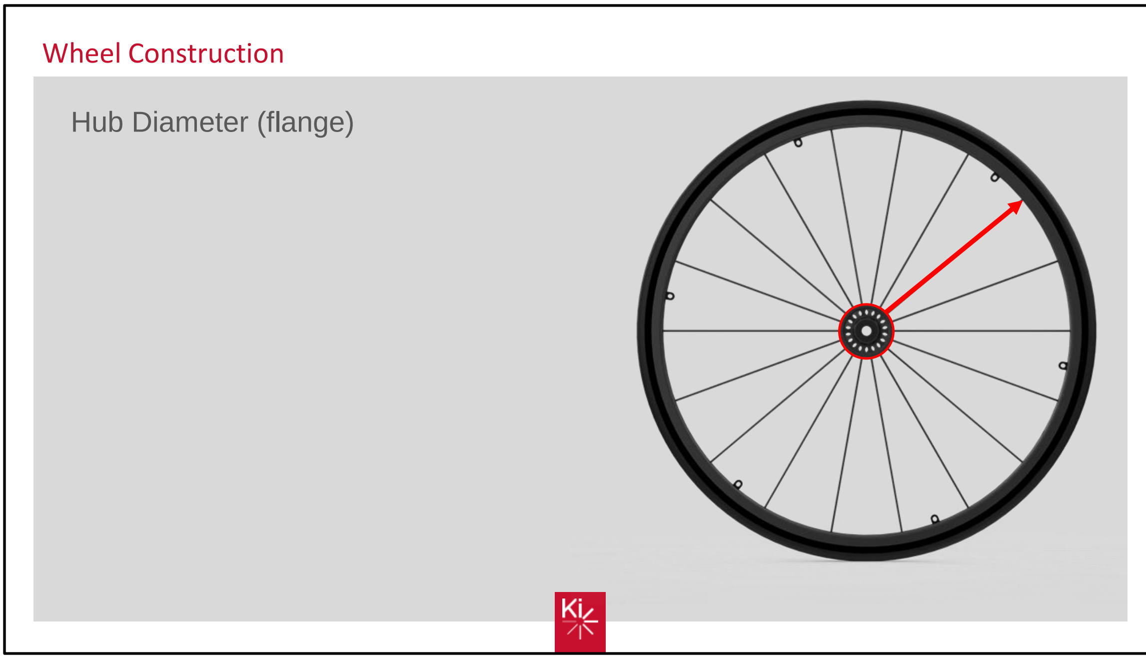
Weight bearing in the wheel is from the 'top' of the wheel, suspending the hub, like suspension wires on a bridge or a trapeze
Good, better, best: entry level, mid-range and high end spoke wheels - consider budget and environment of use – durability
e.g. Spinergy CLX, at high end spoke wheels consider budget and environment of use - durability

Wheel Construction

Hub Diameter (flange)



A smaller diameter hub or hub flange for a given wheel diameter means that the spokes will be longer. This may result in a wheel that has more lateral flex compared to one with larger diameter hub and shorter spokes.



A larger diameter hub or hub flange for a given wheel diameter means that the spokes can be shorter. This results in a stiffer wheel that doesn't flex laterally as much as one with longer spokes.

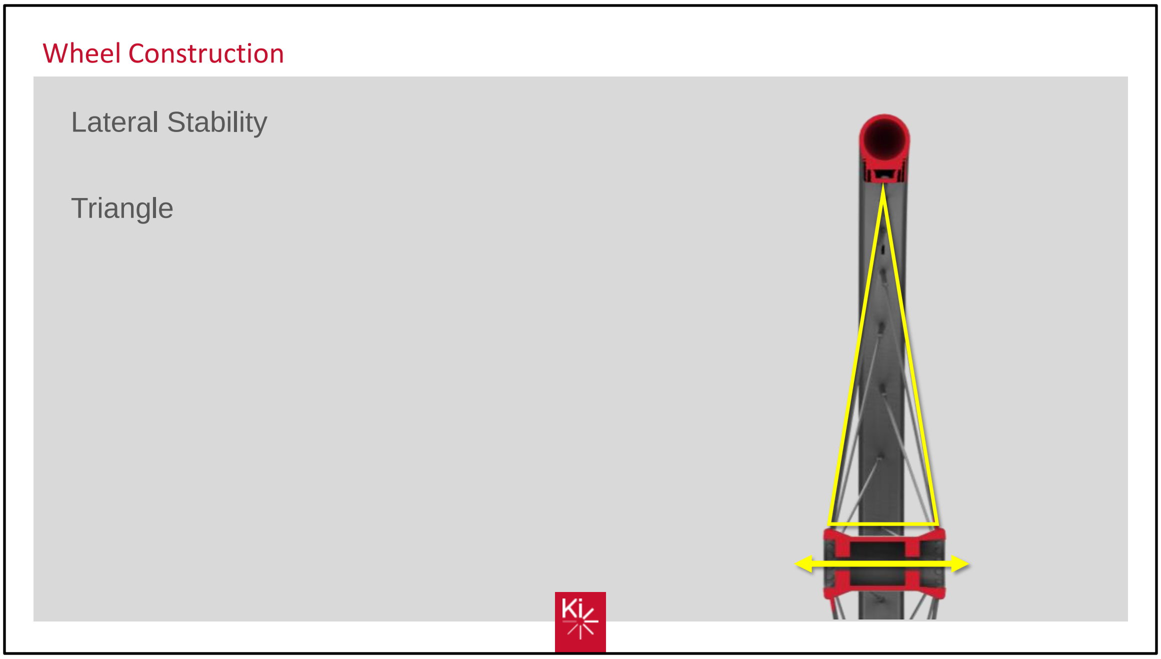
This stiffness, as well as how the spokes are 'laced' (radial, criss-cross, etc.), can result in improved handling during turning, and better transmission of torque from user input on handrim to effecting the rotation of the hub.

Wheel Construction

Lateral Stability

Triangle

Zoom in to next slide
The hub and spokes form a triangle that results in a ‘rigid’ structure and lateral stiffness (resistance to lateral flex). Wider hub flange = shorter spokes. Wider hub = wider base of triangle, but also wider wheel setting.



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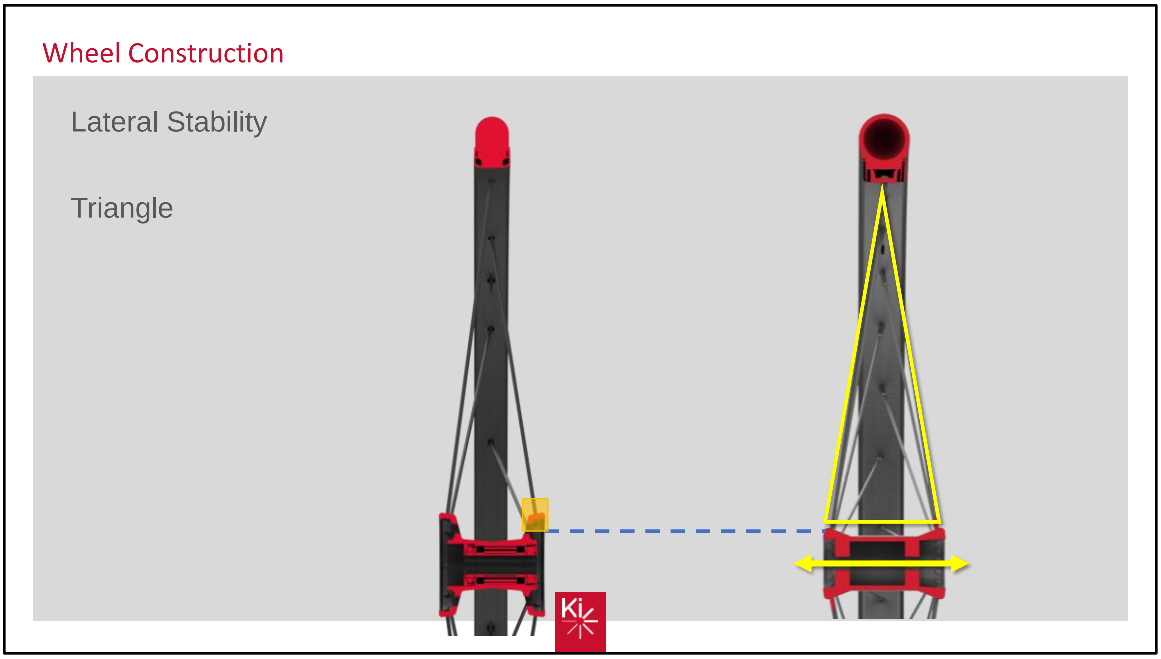
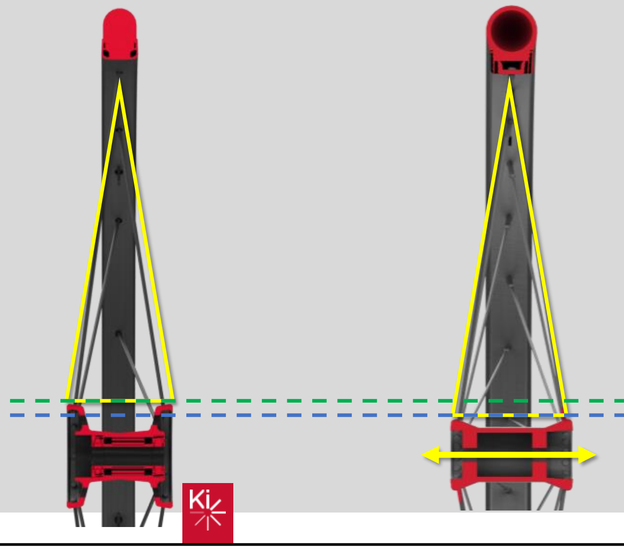


The hub and spokes form a triangle that results in a ‘rigid’ structure and lateral stiffness (resistance to lateral flex). Wider hub flange = shorter spokes. Wider hub = wider base of triangle, but also wider wheel setting.
The difference in the two triangles is reflective of the differences in lateral stability

Wheel Construction

Lateral Stability

Triangle



The hub and spokes form a triangle that results in a ‘rigid’ structure and lateral stiffness (resistance to lateral flex). Wider hub flange = shorter spokes. Wider hub = wider base of triangle, but also wider wheel spacing.

The difference in the two triangles is reflective of the differences in lateral stability

Wheel Construction

What about the difference in various spoke wheels?

Reported advantages to higher end spoke wheels

- Improved lateral and torsional stiffness
- Better energy transfer
- Lighter weight rims/spokes = less rolling mass
- Better performance over a longer time span (e.g. stay true)

Good, better, best: entry level, mid-range and high end spoke wheels - consider budget and environment of use – durability

High end wheels may do better at returning energy input. It may tie to characteristics like flex, lateral stability, rim deformation (hysteresis), etc.

e.g. Spinergy CLX carbon wheels

So, What is the Best Wheel to Select?

Ki

There is no easy button. You need to consider the individual circumstance before you at the moment. . .

So, What is the Best Wheel to Select?

Measurement of Rolling Resistance and Scrub Torque


Assistive Technology
The Official Journal of RESNA

Measurement of rolling resistance and scrub torque of manual wheelchair drive wheels and casters

Stephen Sprigle, Morris Huang & Jacob Misch

Sprigle, Huang and Misch, 2019

In another presentation we discussed this study that looked at RR and scrub torque. We've defined RR, but haven't really mentioned scrub torque until now. . .

So, What is the Best Wheel to Select?

What Is Scrub, or Scrub Torque?

The frictional force that occurs at the tire-surface interface during turning

- Also represents a loss of energy

Sprigle, Huang and Misch, 2019

In rear wheels and casters, at some point, they are not rolling, but turning
When a wheel is turning, it is experiencing some level of scrub torque, and the important point is that this also represents loss of energy

So, What is the Best Wheel to Select?

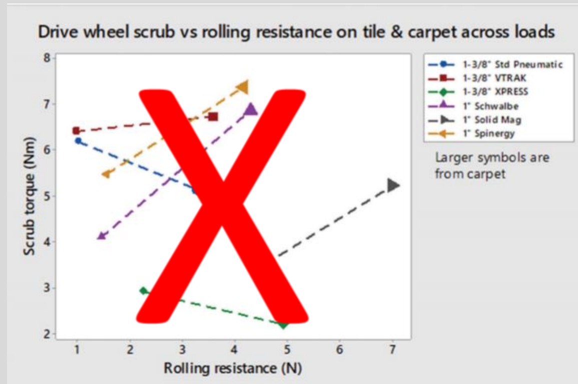
Measurement of Rolling Resistance and Scrub Torque

Results:

There is no perfect drive wheel for all surfaces

Drive wheels are more sensitive to load

Shifting more load onto the drive wheels is the most effective means of reducing resistance



Sprigle, Huang and Misch, 2019

Don’t worry about the data showing data points all over, looking at RR and Scrub T.
Just know the gist – there is no perfect drive wheel for all surfaces
DW are more sensitive to load, and shifting more load onto the DW is the most effective means of reducing resistance

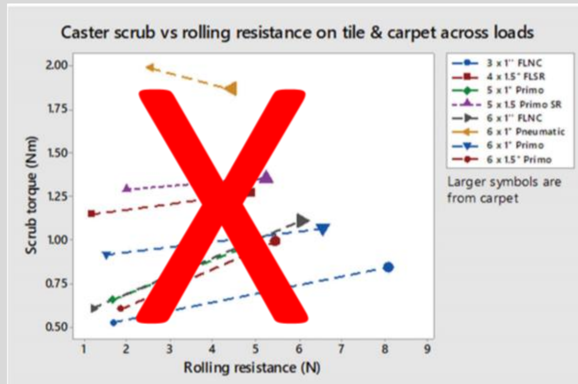
So, What is the Best Wheel to Select?

Measurement of Rolling Resistance and Scrub Torque

Results:

There is no perfect caster for all surfaces.

Caster selection became insignificant when 80% of the load was on the drive wheel



Sprigle, Huang and Misch, 2019

Like the previous slide, don't worry about the data showing data points all over, looking at RR and Scrub T. Just know the gist – there is no perfect caster for all surfaces

We do not measure in clinic, and may not achieve 80%.
The importance of understanding the concept is still there: the more you can bring the rear axle under the user, the more efficient the chair will be – you just need to keep in mind that you can't 'sacrifice' stability (e.g. pitch, or rearward stability).

So, What is the Best Wheel to Select?

Caster Size and Rolling Efficiency

Effect of Caster Wheel Diameter and Mass Distribution on Drag Forces in Manual Wheelchairs

"Weight distribution contributed more to [rolling resistance] regardless of casters used"


JRRD

The effect of caster wheel diameter and mass distribution on drag forces in manual wheelchairs

Study by Zepeda, Chan and Sawatsky corroborates this as well, as do other studies. Used ULW on treadmill, looked at 4", 5" and 6" casters, with weight distributions of 10/90 (caster/rear) through to 60/40 in 10 percent increments.

So, What is the Best Wheel to Select?

Caster Size and Rolling Efficiency

Effect of Caster Wheel Diameter and Mass Distribution on Drag Forces in Manual Wheelchairs

. . .Caster size will not bring any significant difference in the drag force if the wheelchair user has 70% or more of system weight supported by the rear wheels

Zepeda, Chan and Sawatsky, 2016


JRRD

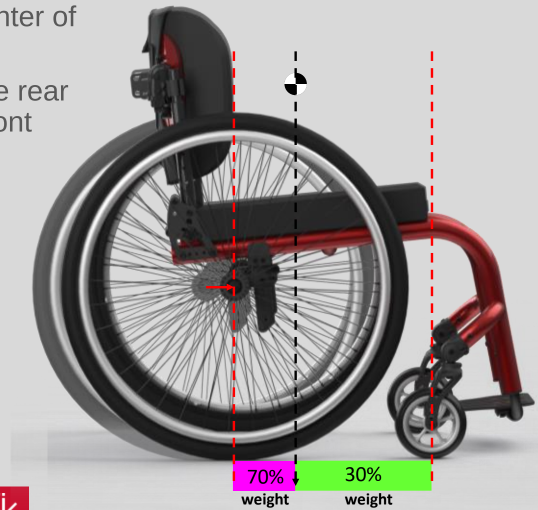
The effect of caster wheel diameter and mass distribution on drag forces in manual wheelchairs

Study by Zepeda, Chan and Sawatsky corroborates this as well, as do other studies. So, Sprigle, Huang and Mische said 80% on the DW, this one says 70% - the point is. . . Shift weight onto the Drive Wheels as much as you can safely do.

So, What is the Best Wheel to Select?

Weight Distribution – also known as Center of Gravity (CG)

The proportion of **system** mass over the rear wheels as compared to that over the front wheels



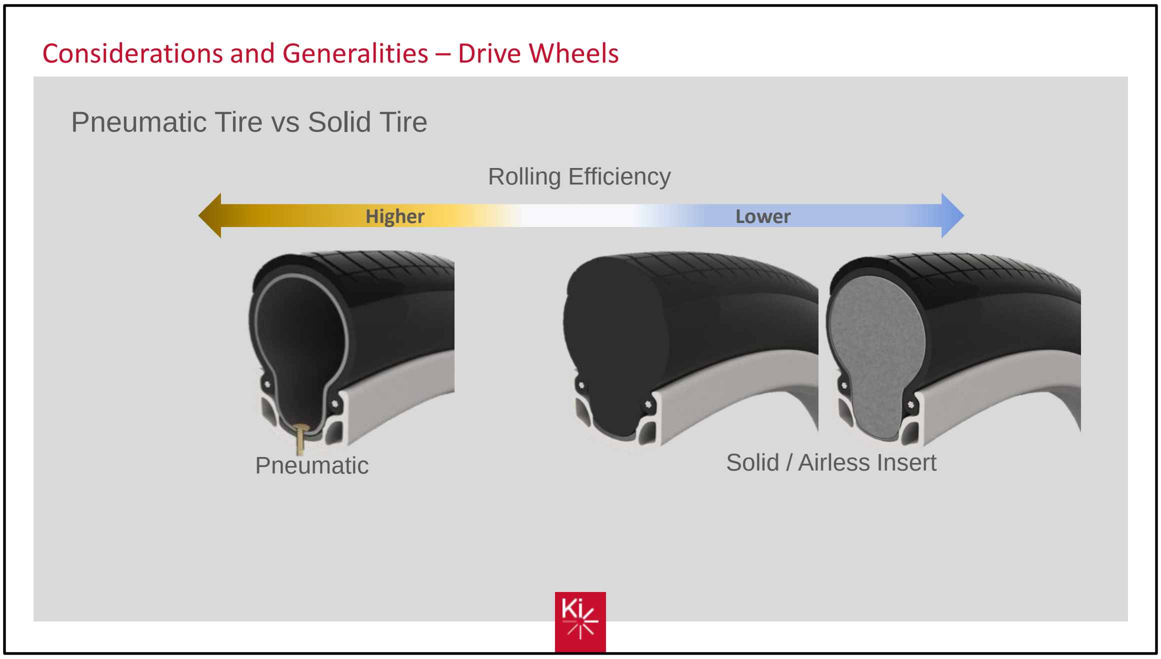
We saw this when we discussed weight distribution/CG earlier.

Quick recall of principle of weight distribution.

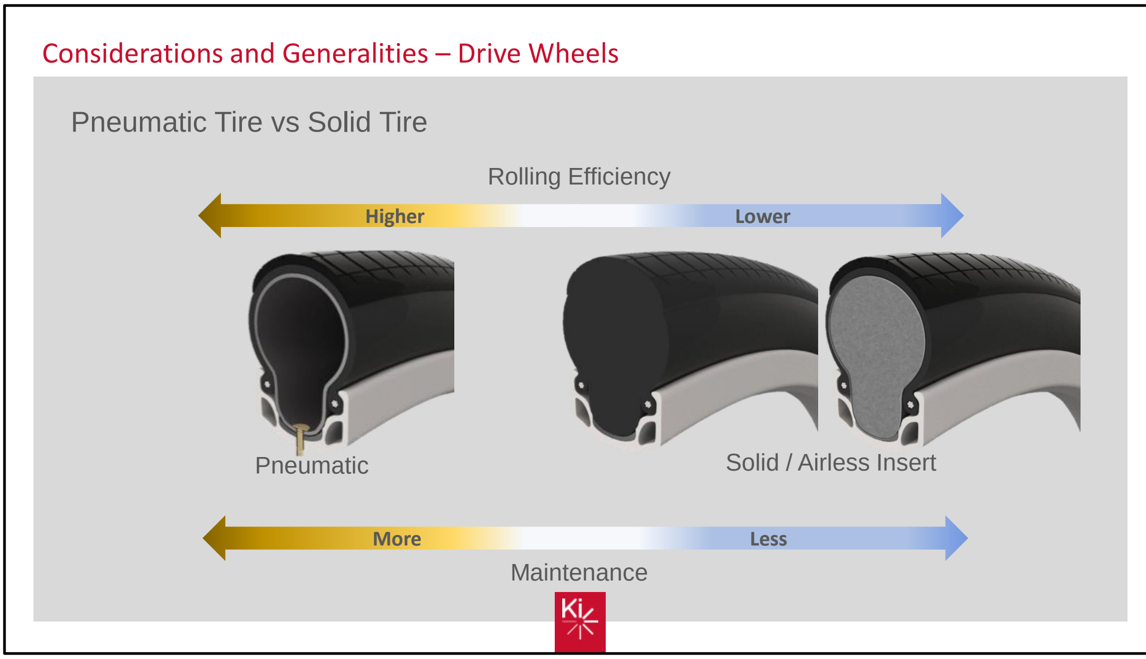
If there is no perfect wheel, then what do I need to consider?

Let's look at some general considerations. . .

Drive Wheels



Consider:
Maintenance – will someone monitor and maintain pressure?
Is environment of use appropriate for a pneumatic tire? Are there thorns, for example?



Consider:
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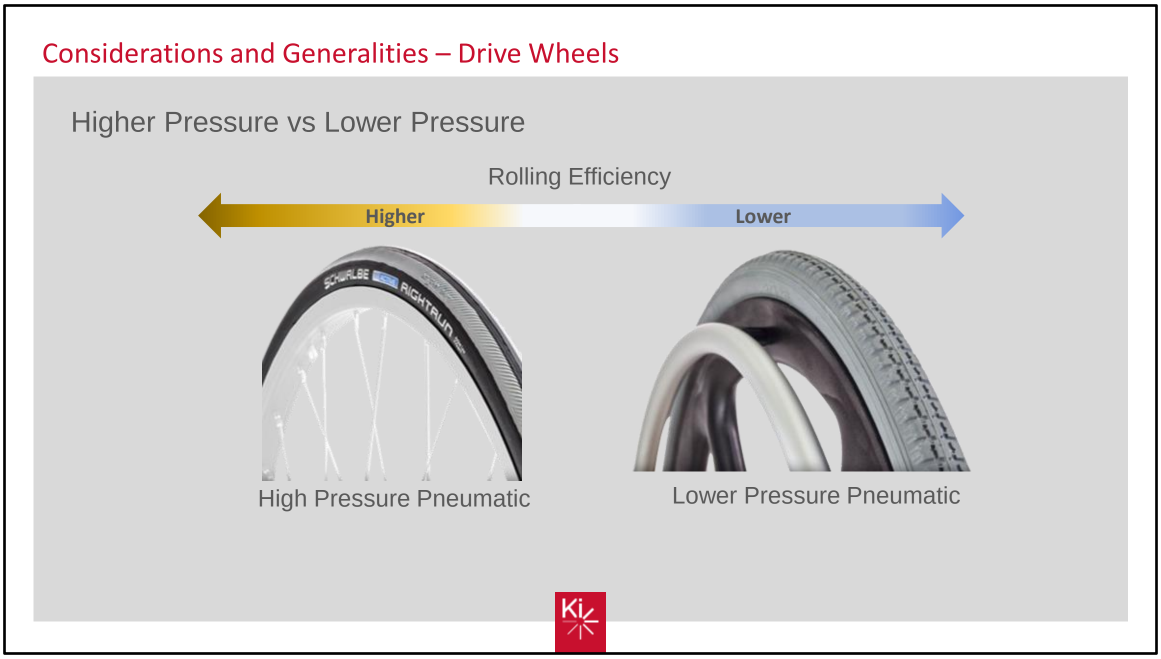
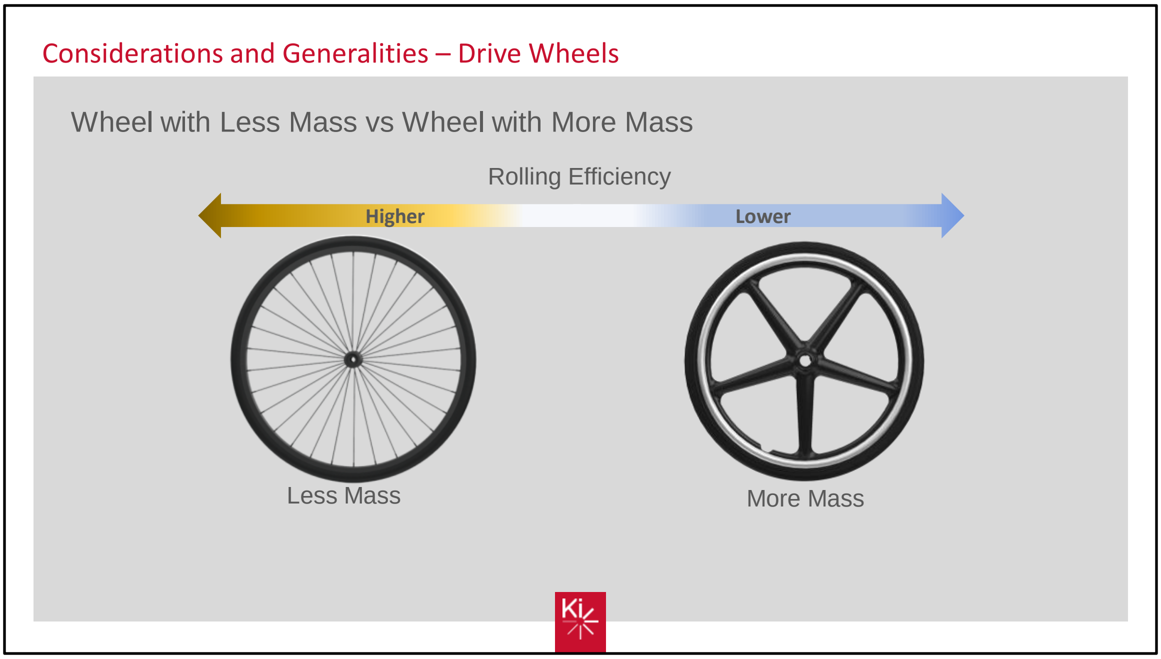


High pressure equates to a ‘harder’ tire that deforms less under a given force (pressure=force/area)



Essentially this is a Spoke Wheel vs Mag Wheel
Consider:
Maintenance capabilities
Transport needs
Concerns or issues of durability

Considerations and Generalities – Drive Wheels

Wider Contact Patch (tire) vs Narrower Contact Patch (tire) – At Same Pressure!

Rolling Efficiency

Higher ⟷ Lower

Wider Contact Patch

Narrower Contact Patch

A Wider tire will float better on soft surfaces

Considerations and Generalities – Drive Wheels

Wider Contact Patch (tire) vs Narrower Contact Patch (tire) – At Same Pressure!

Rolling Efficiency

Higher ⟵⟶ Lower

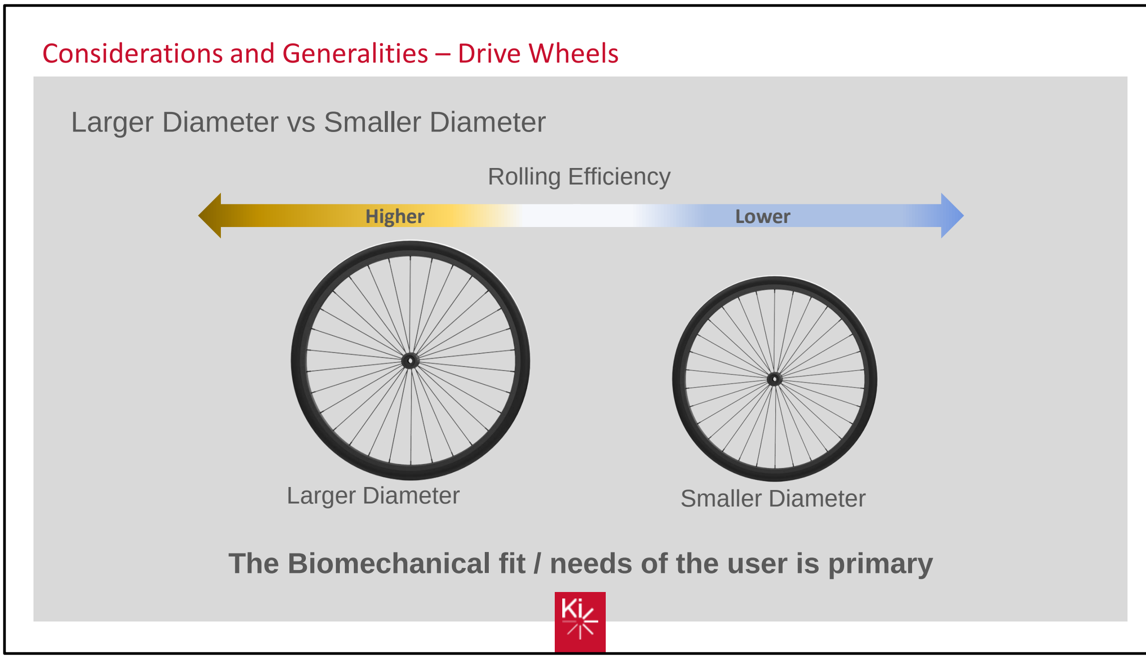
Wider Contact Patch

Narrower Contact Patch

More ⟵⟶ Less

Floatation

A Wider tire will float better on soft surfaces



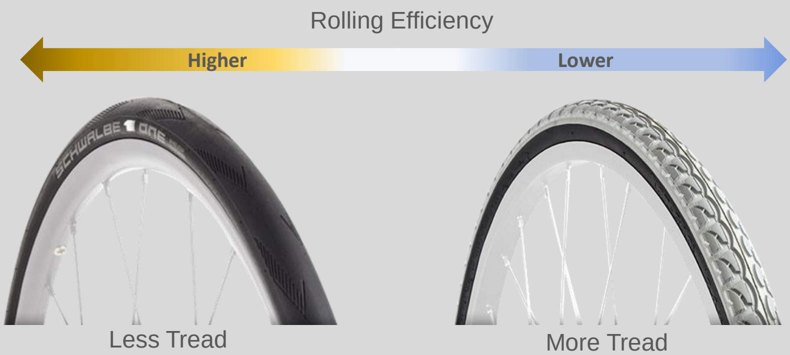
Although larger diameter wheels have less rolling resistance than smaller diameter, **The Biomechanical fit / needs of the user is primary**

Consider:

> Larger diameter wheel has a greater moment of inertia, *but can also provide greater leverage*

Considerations and Generalities – Drive Wheels

Less Tread vs More Tread



More tread on uneven surfaces, as in offroad, dirt, can still be advantageous

Considerations and Generalities – Drive Wheels

More tread on uneven surfaces, as in offroad, dirt, can still be advantageous

Considerations and Generalities – Drive Wheels

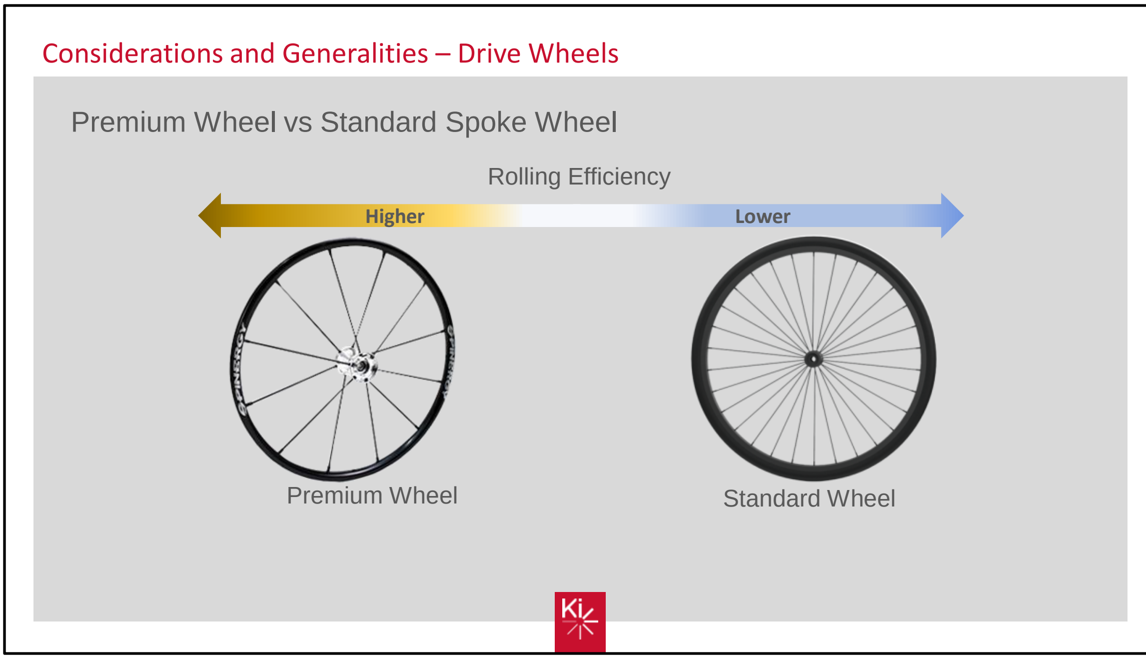
Tread – How Much is Necessary?

A benefit would exist if wheelchair users were provided with [an additional] set of tires [or wheels] – one that has optimal performance indoors and on hard outdoor surfaces, and another that offers traction needed in inclement weather or when traveling on soft terrain.

Assuming a single tire can perform equally well under all conditions and on all surfaces is a fallacy and is not reflected in car or bike tires, which are regularly chosen by their context of use.

(Sprigle, Huang 2019)

For example, a very low drive wheel scrub torque . . . may negatively impact wheelchair traction during turning at relatively higher speeds which may result in sliding. Similarly, for persons needing traction while negotiating soft (e.g. sand) or wet surfaces, a tire with a more pronounced tread pattern may be advantageous even if it results in greater energy loss



Reported advantages to higher end spoke wheels
Improved lateral and torsional stiffness
Better energy transfer
Lighter weight rims/spokes = less rolling mass
Better performance over a longer time span (e.g. stay true)

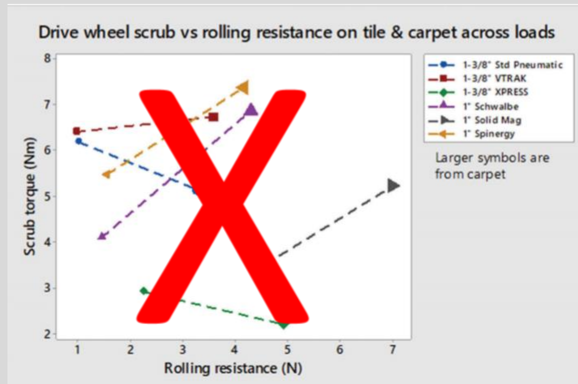
Considerations and Generalities – Drive Wheels

All Things Considered. . .

There is no perfect drive wheel for all surfaces

Drive wheels are more sensitive to load

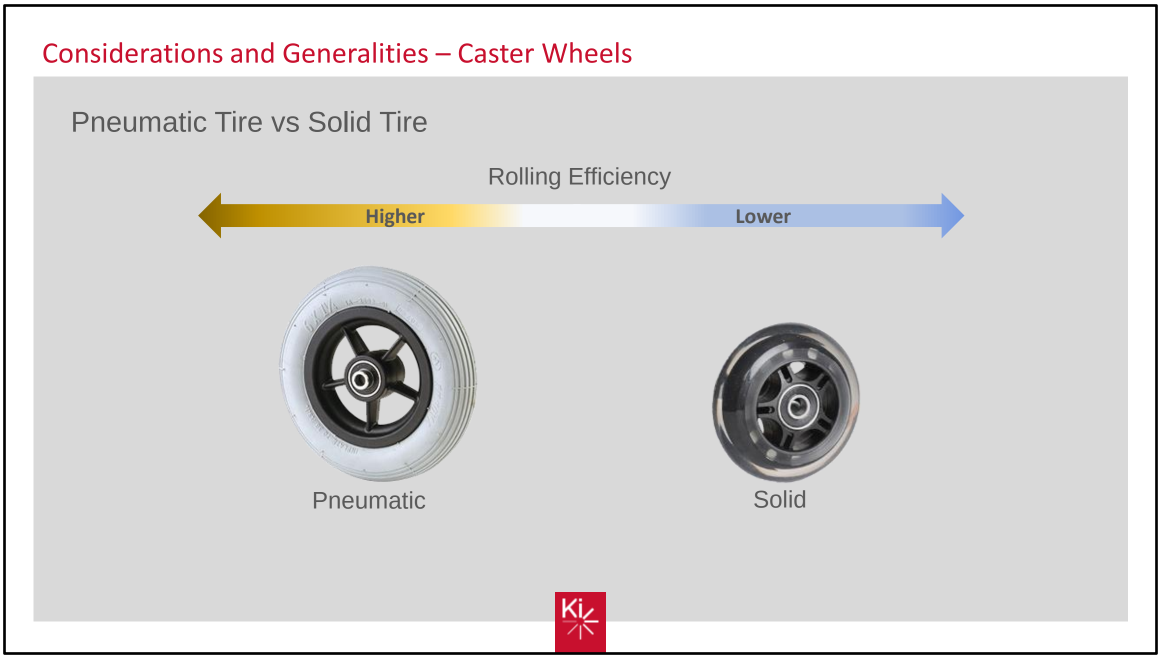
Shifting more load onto the drive wheels is the most effective means of reducing resistance



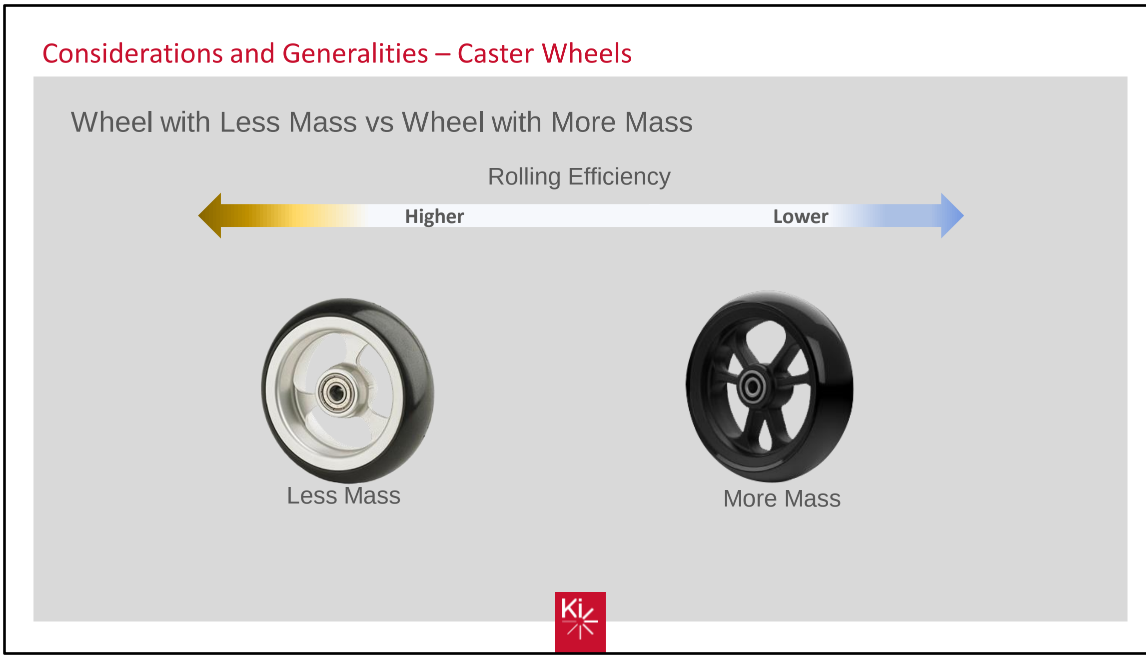
Sprigle, Huang and Misch, 2019

Remember that we said the DW are more sensitive to load, and shifting more load onto the DW is the most effective means of reducing resistance

Caster Wheels



Consider:
A little bit of air loss goes a long way on a small wheel [proportionality] Losing 50 cc of air is a ~3.9% reduction for a 24” tire, and a ~54% for a 6”
Maintenance – will someone monitor and maintain pressure?
Is environment of use appropriate for a pneumatic tire?
As a practical matter, pneumatic casters tend to only be available in larger sizes e.g. 6” or 8” (maybe 5”), and they can come with challenges (more sensitive to air loss, fewer choices, no need for traction, etc.)
Environment of use may matter much. Story of gentleman who had to cross railroad tracks multiple x/day to commute to/from work – selected large pneumatic casters for that reason.



-Lighter product is not always the best product – quality of tire material in terms of energy return may mean that a more dense material (polyurethane) weighing more, provides better energy return due to lower hysteresis losses

-Mass of caster wheels is about an order of magnitude smaller than drive wheels. For example, 0.12 kg for a caster vs 1.71 for a drive wheel

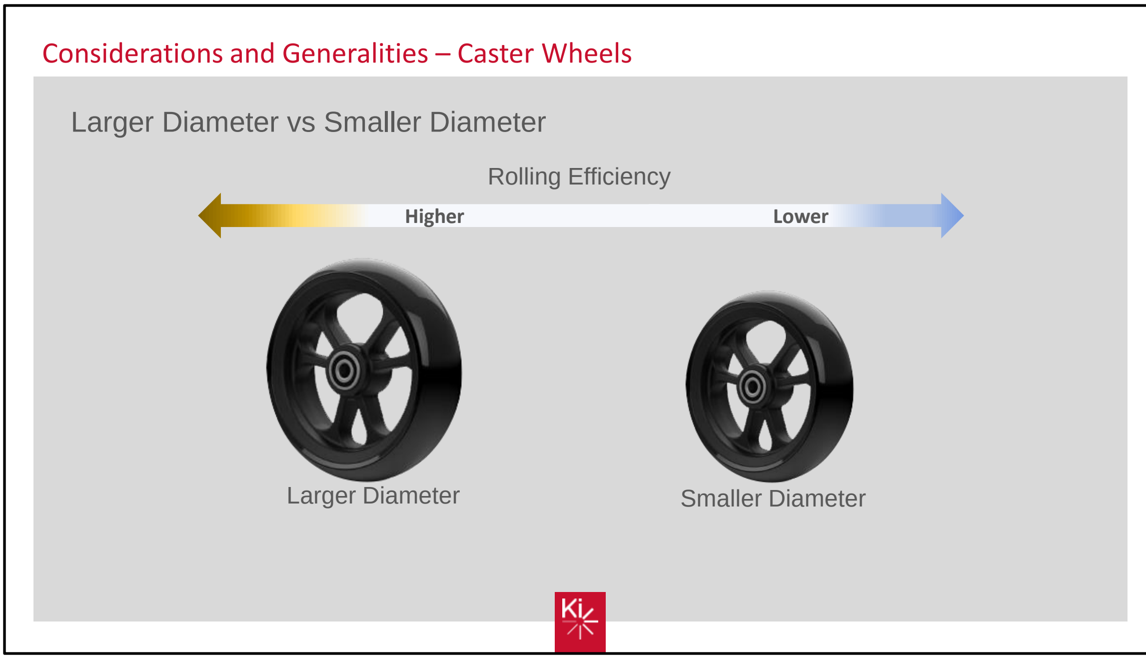
However, when comparing these components to the overall mass of the MWC system (approximated

as 100 kg), the drive wheels and casters each only account, at most, 4% and 0.8% of the system mass, respectively,

indicating that the benefits gained from a lighter caster or drive wheel are minute.

Sprigle, Huang 2019

Mass of caster wheels is only ~0.8% of system mass (system mass of ~100 kg), and even though there are differences in rotational inertia between caster wheels, the overall impact due to rotational inertia is minimal



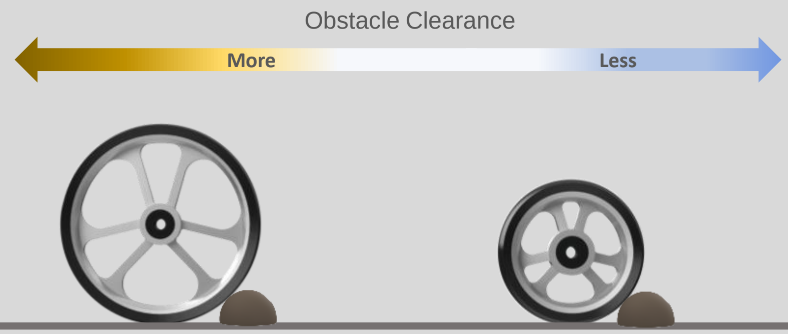
Caster wheels catch on gravel, a peanut on the floor, a raisin, etc. Smaller ones more so than larger ones.
Casters do not follow the trend of greater rolling resistance with decreasing diameter (Sprigle, Huang 2019), but this was a small *n* with variations not only in diameter, but width, profile and hardness.

All of these factors influence

wheel contact surface which, in turn, influences rolling resistance.
In another study, Kauzlarich and Thacker acknowledged that RR is inversely proportional to radius (slide 79)

Considerations and Generalities – Caster Wheels

A larger wheel rolls over obstacles more easily than a smaller wheel



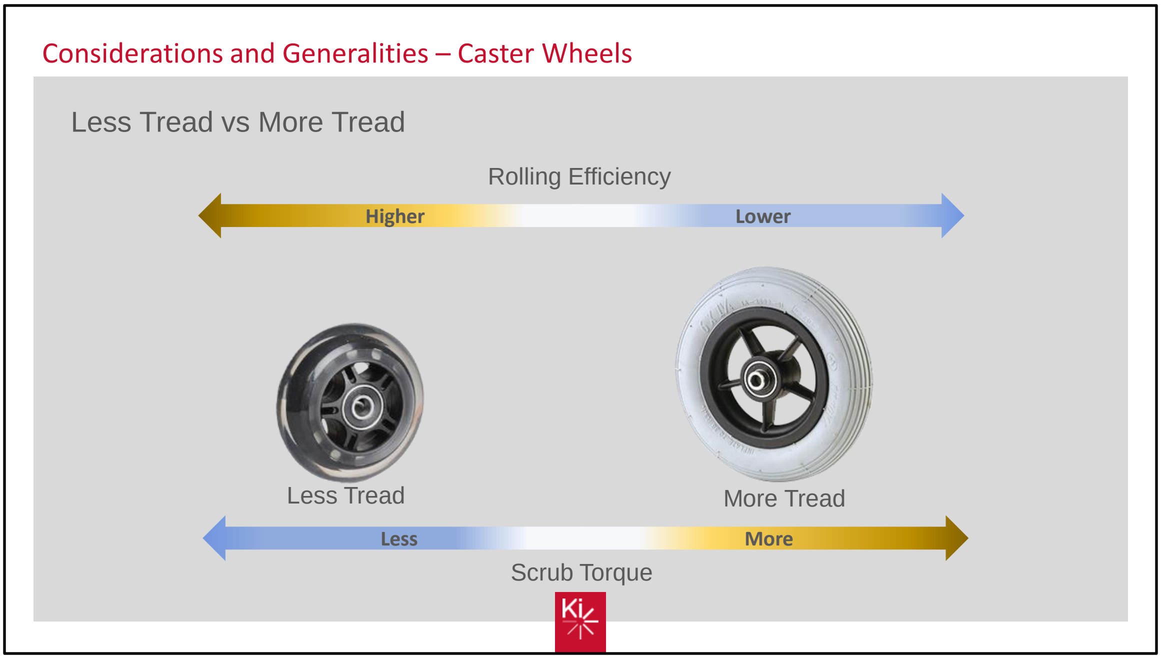
Consider wheelchair skills – can/does the person perform a wheelie to clear obstacles, or do they hit it 'head on'?

A larger wheel rolls over obstacles more easily than a smaller wheel. An extreme example is how a small obstacle can stop a caster wheel (even like on a grocery cart), but a large rear wheel rolls right over it without even much of a 'bump'

Obstacles could be an upward protrusion such as a threshold, or it could be a downward one, such as a seam in concrete.

When a wheel makes contact with a square-edge obstacle, the contact angle = the angle of the tangent of the wheel at point of contact with the square edge obstacle and the horizontal as shown above.

https://www.evo.com/guides/mountain-bike-wheel-size



Consider:

Caster wheel is passive, it's 'along for the ride'

Because it's passive, it doesn't contribute to drive/traction

Tread may increase scrub

Most caster tires are smooth, with a few that are ridged
The ridges may be for longer rubber life, but not with a weight penalty of thicker and solid
Want it as close to a sphere as possible – like a trac ball

Considerations and Generalities – Caster Wheels

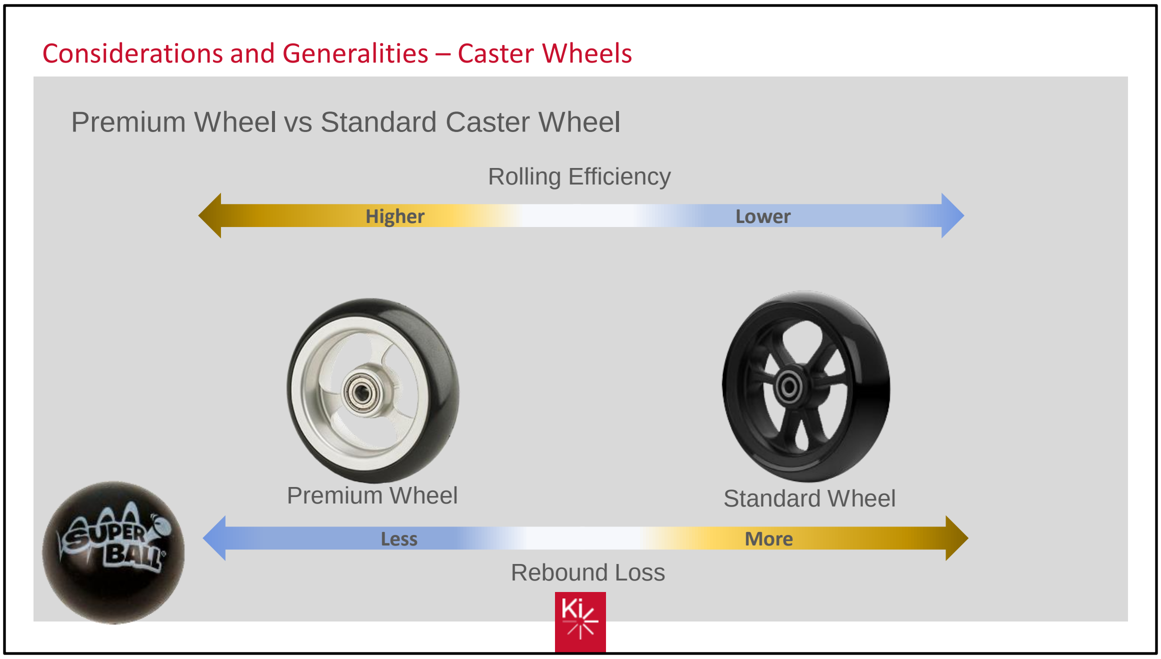
Premium Wheel vs Standard Caster Wheel

Rolling Efficiency

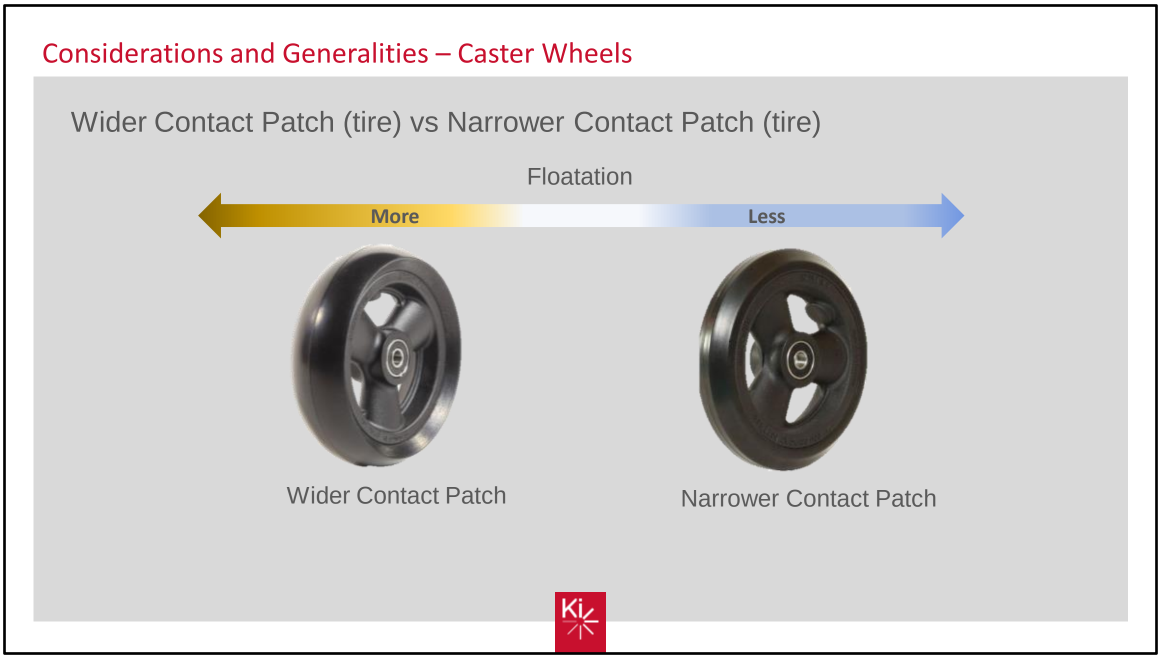
Higher ⟷ **Lower**

Premium Wheel

Standard Wheel



Reported advantages to higher end caster wheels
Improved true 'roundness' for balance
High-rebound polyurethane 'recipe' designed to minimize energy loss and absorb vibration.
minimizes air bubbles in the tread, resulting in a denser material, fewer defects, and less tread damage compared to when air bubbles in other wheels are uncovered from wear or impacts
Better performance over a longer time span (e.g. stay true)



A Wider tire will float better on soft surfaces

A Wider tire will float better on soft surfaces

Considerations and Generalities – Caster Wheels

Caster Width and Shape

Let's look at one advantage of the domed profile of some casters. . .

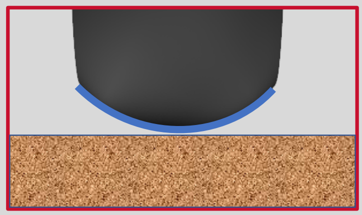
Considerations and Generalities – Caster Wheels

Caster Width and Shape

Zoom in

Considerations and Generalities – Caster Wheels

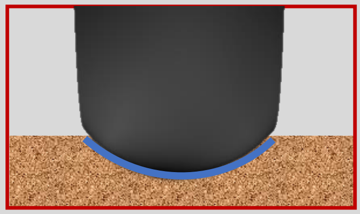
Caster Width and Shape



We see this rounded, domed, shape.

Considerations and Generalities – Caster Wheels

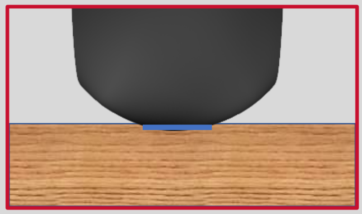
Caster Width for Floatation on Soft Surfaces



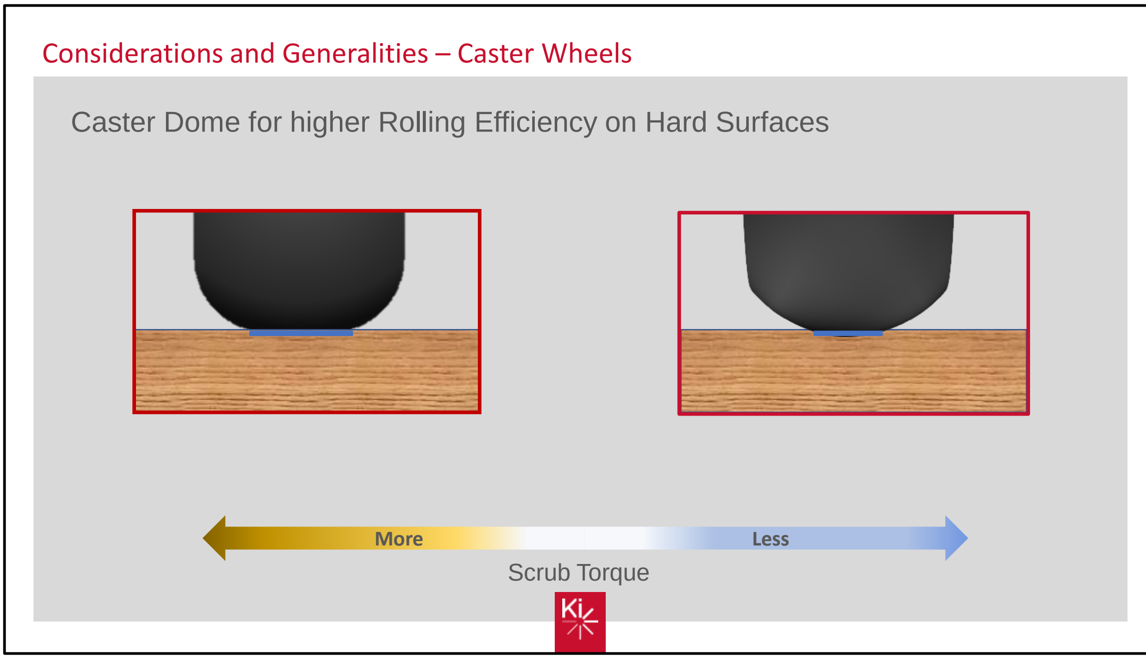
As the domed profile sinks into a soft surface, more and more of the width of the tire is engaged to produce some floatation in the soft surface

Considerations and Generalities – Caster Wheels

Caster Dome for higher Rolling Efficiency on Hard Surfaces



However, on a more firm surface, a relatively small amount of surface area is in contact with the floor (small contact patch), thus resulting in minimal scrub torque



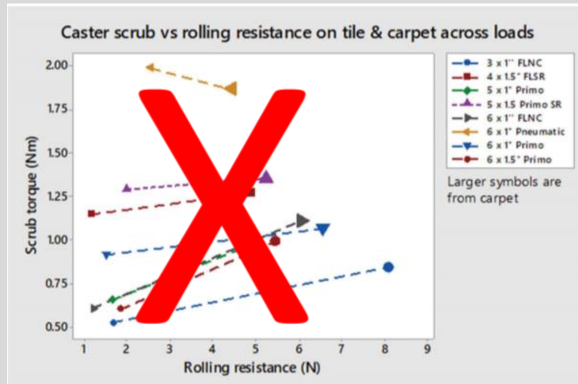
More of the tire in contact with the surface can mean the possibility for more scrub because of it (given same materials/compound)

All Things Considered. . .

All Things Considered. . .

There is no perfect caster for all surfaces.

Caster selection became insignificant when 80% of the load was on the drive wheel



Sprigle, Huang and Misch, 2019

Remember what we said about caster selection becoming relatively insignificant when we can achieve 80% load on DW?

The Wheel Story

Let's Revisit the Wheel Story we began with. . .

So, let's talk about . . . The Wheel Story

The Wheel Story

Knowing what you know now. . .

- Would you still select those mag wheels and airless inserts?
- Would you reason it through any differently?
- Were the factors considered in the proper context?

So, knowing what you know now, would you still select those mag wheels? Would you reason it through any differently? Did you consider the factors in the proper context?

Soapbox

Soapbox

Why did we discuss all this?

Everyone seems to agree that we need to preserve UE of mwc users – the problem is not everyone gets “how do we do that?”

Our position is that it’s not just by selecting the lightest weight wc –

You do that by

- Proper Prescription
- Component Selection
- Setup and Adjustment . . .
- and Training.

Thank You

?

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