Total System Efficiency™

Making you faster

You want as much speed as your body and bicycle will allow. The following pages will help you understand how Zipp wheels make you faster than ever over terrain both smooth and rough. With the right setup, wheels designed using Total System Efficiency can increase cycling speed by 5% for the same power.

What is it?

At the core of Total System Efficiency (TSE™) lies the notion that sometimes you must give up narrowly focused perfection to achieve the optimum of a whole system. Everything is interconnected - changing one part of the rider-bicycle system will affect other parts. The sole pursuit of minimum weight or aerodynamic drag *at the neglect of other details* can result in a net decrease in cycling speed. The ability of a bicycle wheel to affect cycling speed is defined by the sum of every influence it has on the rest of the system.

Efficiency = Speed

Maximizing the speed of a cyclist is about making the most efficient rider-bicycle system. An increase in system efficiency will achieve more speed for the same power input. Which factors determine speed?

According to Newton's Third Law of Motion, the sum of forces pushing a cyclist down the road are matched by the sum of forces impeding progress. This is commonly written as a force balance equation – where the forces on each side must balance each other.

$$\boldsymbol{F}_{(+)} = \boldsymbol{F}_{(-)}$$

propulsive forces match the impeding forces

A deeper look at the components of propulsive and impeding forces shows:

$$\boldsymbol{F}_{(+)} = \boldsymbol{F}_{tire}$$

tangential force of the rear tire pushing the cyclist along

$$\boldsymbol{F}_{(-)} = \boldsymbol{F}_{wind} + \boldsymbol{F}_{gravity} + \boldsymbol{F}_{rolling} + \boldsymbol{F}_{vibration} + \boldsymbol{F}_{inertia}$$

principal impeding forces acting on a cyclist

While comparisons of force are intuitive to conceptualize, most cyclists today relate best to power measured in watts. The forces can be converted to power by multiplying each force term by bicycle speed, $\boldsymbol{v_b}$:

$P_{tire} = v_b F_{tire} = P_{crank} c_{loss}$	*cyclist-generated power transferred to the rear tire*
$P_{wind} = v_b F_{wind} = v_b \frac{1}{2} \rho {v_w}^2 C_d A$	*aerodynamic power*
$P_{gravity} = v_b F_{gravity} = v_b mg \sin(\theta)$	*work rate of gravity (negative when riding downhill)*
$P_{rolling} = v_b F_{rolling} = v_b c_{rr}\, mg \cos(\theta)$	*rolling power*
$P_{vibration} = v_b F_{vibration} = \cancel{v_b} \frac{P_{abs}}{\cancel{v_b}}$	*absorbed power ($F_{vibration}$ in the direction of travel)*
$P_{inertia} = v_b F_{inertia} = v_b a(m + \frac{I}{r^2})$	*power lost to acceleration in the direction of travel*

Referring to the original force balance equation can yield a power balance equation:

$$P_{tire} = P_{wind} + P_{gravity} + P_{rolling} + P_{vibration} + P_{inertia}$$

With the long-form equation showing all the definitions relating to $\boldsymbol{P_{crank}}$:

$$P_{crank} = \frac{v_b}{c_{loss}} \left(\frac{1}{2} \rho {v_w}^2 C_d A + mg \sin(\theta) + c_{rr}\, mg \cos(\theta) + \frac{P_{abs}}{v_b} + a(m + \frac{I}{r^2}) \right)$$

A bicycle wheel can affect five terms from the equation. A wheel designed with TSE™ will balance these factors to achieve maximum speed:

$C_d A$	*(coefficient of drag) x (reference area)*
m	*rider-bicycle system mass*
I	*wheelset rotational moment of inertia*
c_{rr}	*coefficient of rolling resistance*
P_{abs}	*absorbed power*

$$P_{crank} = \frac{v_b}{c_{loss}} \left(\overbrace{\frac{1}{2} \rho {v_w}^2 C_d A}^{F_{wind}} + \overbrace{mg \sin(\theta)}^{F_{gravity}} + \overbrace{c_{rr}\, mg \cos(\theta)}^{F_{rolling}} + \overbrace{\frac{P_{abs}}{v_b}}^{F_{vibration}} + \overbrace{a(m + \frac{I}{r^2})}^{F_{inertia}} \right)$$

Solving the equation for speed describes the relationship between speed and the rider-bicycle system:

$$v_b = \frac{P_{crank} c_{loss}}{\underbrace{\frac{1}{2}\rho {v_w}^2 C_d A + mg\, sin(\theta) + c_{rr}\, mg\, cos(\theta) + \frac{P_{abs}}{v_b} + ma}_{F_{(-)}}}$$

Condensing all the terms for impeding forces back into the umbrella term $F_{(-)}$ arrives at:

$$v_b = \frac{P_{crank} c_{loss}}{F_{(-)}}$$

This final equation brings the initial description of Total System Efficiency back into focus. For a fixed power input at the crank, cycling speed is inversely proportional to the sum of impeding forces. This means, for example, a 10% reduction of impeding forces leads to a 10% increase in speed. We will expand on each of the principal losses cyclist experience to fully appreciate how a wheel can reduce these forces and increase cycling speed.

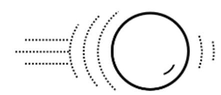
"A 10% reduction of impeding forces leads to a 10% increase in speed."

Wind Resistance

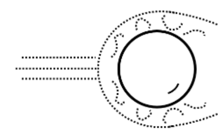
$$P_{wind} = v_b \frac{1}{2} \rho v_w{}^2 C_d A$$

The force coefficient $C_d A$ is made up of two terms, a shape factor C_d, multiplied by a scale factor of projected frontal area A. Coefficent of drag, C_d , encapsulates two main types of aerodynamic drag - induced drag (drag due to lift) and parasitic drag. For bicycles, induced drag occurs when wind approaches at yaw. Parasitic drag can further be separated into three distinct forms:

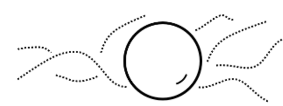
- *Form drag* is the pressure differential between the leading and trailing surfaces of a rider-bicycle system. Flow attachment or separation has a large influence on form drag.



- *Friction drag* is viscous shear of air against the rider and bicycle and is influenced by flow type; laminar vs. turbulent, attached vs. separated.



- *Interference drag* is any aerodynamic loss created by a system of components near one another. Component interaction determines the magnitude of interference drag.



Zipp’s wind tunnel experience exceeding 1,000 hours of testing across three decades shows that aerodynamic bicycle wheel designs, categorically, have diminishing returns with further refinements towards form drag or friction drag of the rim alone. While tire shape is essentially fixed to a semi-circular cross-section, overall C_d improvements are still possible by refining the surface transition between tire and rim, forming a more aerodynamic package.

Wheel type	Tire Type	C_dA on road
303 S, MY21	Zipp RT28	0.3134
Old 303 FC, MY20	Zipp RT28	0.3278

Table 1 - Real-world aerodynamic testing of rider-bicycle system by 3rd part testing consultant

Wheels account for approximately 15%[1] of the total drag force of a rider-bicycle system. Improvements made to wheel aerodynamics alone can impact speed by over 4%.

"Improvements made to wheel aerodynamics alone can impact speed by over 4%"

[1] D. Greenwell, N. Wood, E. Bridge, and R. Add, 1995. *Aerodynamic characteristics of low drag bicycle wheels*. The Aeronautical Journal, Volume 99, Issue 983, pp. 109-120.

Gravity

$$P_{gravity} = v_b m g \, sin(\theta)$$

As described by the equation above, $P_{gravity}$ is proportional to the total mass of the rider-bicycle system. Efficiency gains from lighter components are magnified by typically slower speeds riding uphill, which increases the relative proportion of total time spent riding uphill compared to flat or downhill. While road incline also plays a dominant role, there is no way for a cyclist to affect this environmental factor (aside from avoidance altogether). Below is a table to help understand the relationship between $P_{gravity}$, mass, and road incline.

Power (W) required to carry additional mass uphill at 20kph

Additional mass (grams)	Road gradient (%) 0%	2%	4%	6%	8%	10%
100	-	0.1	0.2	0.3	0.4	0.5
200	-	0.2	0.4	0.7	0.9	1.1
400	-	0.4	0.9	1.3	1.7	2.2
800	-	0.9	1.7	2.6	3.5	4.3
1,600	-	1.7	3.5	5.2	7.0	8.7
3,200	-	3.5	7.0	10.4	13.9	17.3
6,400	-	7.0	13.9	20.9	27.8	34.7
12,800	-	13.9	27.9	41.8	55.6	69.4

Figure 1

It is important to note, while mass of the system is most commonly associated with impeding forces of gravity, mass affects all forms of loss except wind resistance. Lowering the mass of the rider-bicycle system decreases rolling resistance, vibration loss, and inertial forces in addition to gravity.

"Mass affects all forms of loss except wind resistance"

Inertia

$$P_{inertia} = v_b a\left(m + \frac{I}{r^2}\right)$$

Inertia is the resistance of mass to changes in speed. When discussing changes of speed for a bicycle wheel, there are two types of inertia we are concerned about – translational inertia and rotational inertia. Translational inertia accounts for the force required to accelerate the mass of an object through space, while rotational inertial accounts for the torque required to spin a mass faster around an axis of rotation. While they are directly linked for a wheel, both types of inertia are acting on an accelerating wheel simultaneously. Below is a figure showing a comparison of power required to accelerate an 85kg bicycle-rider system 1.3m/s^2 starting from 40kph (maximal sprint) while riding the old 303 Firecrest® wheels and while riding the new model year 2021 303 Firecrest® wheels.

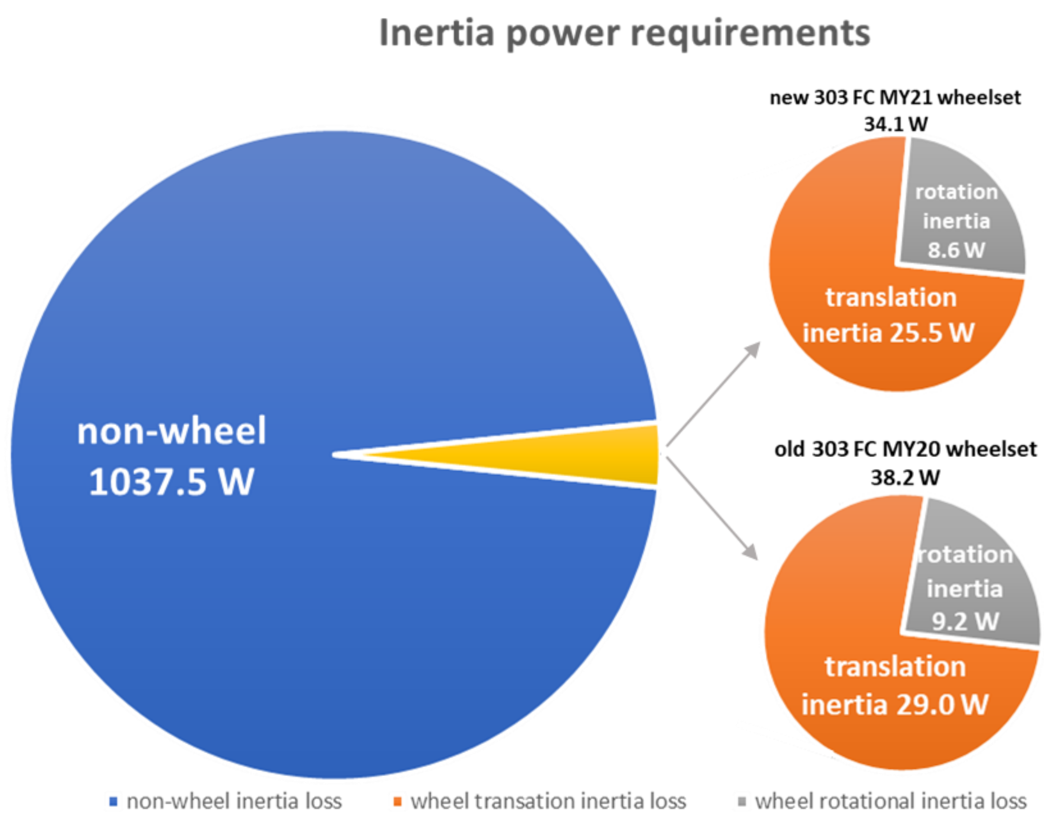


Figure 2 – Left pie chart shows total inertia power, right charts show wheelset-only inertia power for new 303 (top) and old 303 (bottom)

In addition to this efficiency gain, many discerning cyclists will sense a qualitative improvement in a wheel that is 20% lighter and has 23% lower moment of inertia compared to its predecessor.

Wheel model	Wheelset weight (g)	Rotational Inertia (kg-m²)	Inertia difference (%)
303 Firecrest TL DB (MY21)	1355	0.0425	0.0%
303 Firecrest tubular	1372	0.0419	-1.5%
303 S	1540	0.0481	13.1%
303 Firecrest TL DB (MY20)	1655	0.0525	23.5%

Table 2 - Comparison of 303 wheel inertia (single wheel, no tire)

Note that the new tubeless clincher 303 Firecrest is lighter than its tubular counterpart and nearly the same rotational inertia. Additional benefits of lowering wheel inertia include improved braking capability.

In addition to efficiency gains, lower inertia contributes to a perceived improvement in ride quality.

Rolling Resistance $P_{rolling} = v_b c_{rr} mg\cos(\theta)$

What exactly causes rolling resistance? In concept, the idea is simple: as a wheel rotates under the weight of a cyclist a section of tire is pressed flat against the road. Compressing the tire flat takes energy just like compressing a spring. As that section of tire rotates and lifts off the road it springs back to its original shape. The energy lost to rolling resistance is the difference between how much energy was required to form the flat contact patch compared to how much energy the tire returned pushing back into its original shape. The technical term for this phenomenon is called elastic hysteresis. Internal material friction from elastic molecules and components in the tire rub against each other as they get deformed. This friction robs kinetic energy from the system, turning into heat and dissipating into the environment.

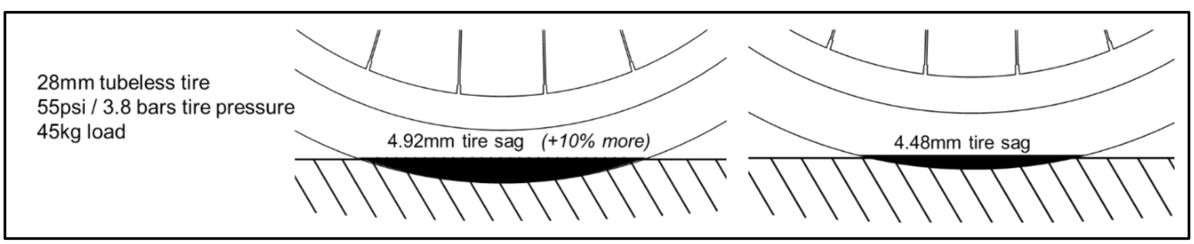
How can we reduce rolling resistance?

Consider two identical tires inflated to equal pressure but mounted on rims with different tire bed widths. Under identical loads each of the tires will experience different amounts of tire sag. The wider rim produces a wider tire, which yields a wider and shorter tire contact patch. Because of how the contact patch shape relates to the curvature of a wheel's outer diameter, a wider and shorter contact patch *deforms the tire less* resulting in less energy lost in the rolling tire and a corresponding jump in efficiency.

The wide tire bed in the 303 S sags 10% less than the previous generation 303, leading to a 9% improvement in coefficient of rolling resistance, c_{rr} . An example in the table below demonstrates the idea of TSE™ – improving the tire interface on a wider rim can result in system gains to both C_dA and $\boldsymbol{c_{rr}}$.

Wheel type	Tire Type	Tire Pressure	Crr on road	CdA on road	Rolling Power (W) @40kph	Aero Power (W) @40kph	Total Power (W) @40kph
303 S, MY21	Zipp RT28	50	0.00421	0.3134	35.7	225.7	261.4
Old 303 FC, MY20	Zipp RT28	50	0.00463	0.3278	39.2	236.1	275.3

Table 3 - Real-world rolling resistance testing by 3rd part testing consultant



"Improving the tire interface on a wider rim can result in system gains to both C_dA and c_{rr}"

Vibration Loss

Concrete velodrome	**175**	watts
Dirt bicycle path	**210**	watts
Cobbles of Arenberg Forest[2]	**339**	watts

Table 4 - power requirement for 92kg system mass riding 35kph over various surfaces

Consider a 92kg bicycle-rider mass traveling 35kph over various surfaces. Intuitively, the required power increases with rougher surfaces. Think of the cobbled sectors of fabled Paris-Roubaix. What is it about the cobbles that causes nearly doubling of power required to maintain the same speed over a smooth surface, like the velodrome finale in Roubaix? Does this same effect occur on less severe roads? How rough of a road warrants changing your bicycle setup? These questions can be answered by understanding vibration loss.

Vibration loss refers to the force opposing forward motion encountered when lifting the rider-bicycle system over small bumps many times per second. This impeding force stems from horizontal and vertical impulses from the road surface, as well as energy lost to the damping response when a human body is shaken. Extra energy is required to lift the entire rider-bicycle mass over millimeters-tall obstacles in the road texture. Above certain thresholds of speed, bump spacing, and bump height, the vast majority of this extra energy is lost. Relative movement between the layers of muscle, connective tissue, and organs causes friction and viscous shearing, which dissipates kinetic energy[3] into heat (think about why your body evolved a shivering reflex in the cold). Whole-body vibration while cycling stems from the inability of a tire to fully deform around bumps. Higher tire pressure leads to more vertical movement of the bicycle and rider. Lower tire pressure helps maintain a constant elevation of the center of gravity by cutting out road input. The real-world examples above show that absorbed power can account for significant losses of efficiency.

Vibration loss changes with surface roughness. How do you measure surface roughness? For the purposes of optimizing a rider-bicycle system towards maximum speed, it is most helpful to measure the *dynamic response* of the system to surface roughness. This dynamic response describes how the rider, bicycle, and tires all interact in a manner characterized by a standard linear solid model defined as a series of masses connected by springs and dampers[3]. Adapting this science to study bicycle dynamics is largely novel, and it relates directly to the goal of designing a wheel that allows cyclists to go as fast as possible over all levels of surface roughness.

"Absorbed power can account for significant losses of efficiency"

[2] Gallagher, S. (2018, April 16). *File analysis: Taylor Phinney at the 2018 Paris-Roubaix.* Training Peaks. https://www.trainingpeaks.com/blog/file-analysis-taylor-phinney-at-the-2018-paris-roubaix/

[3] Xiangyu Xie, 2001. *Absorbed power as a measure of whole-body vehicular vibration exposure*. Condordia University Mechanical Engineering Department. p.36

RollingRoad™ Testing

Zipp developed the RollingRoad™ to better understand the relationship between surface roughness and cycling efficiency. It is a testing apparatus that provides a reconfigurable moving ground plane to recreate specific surface roughness conditions.

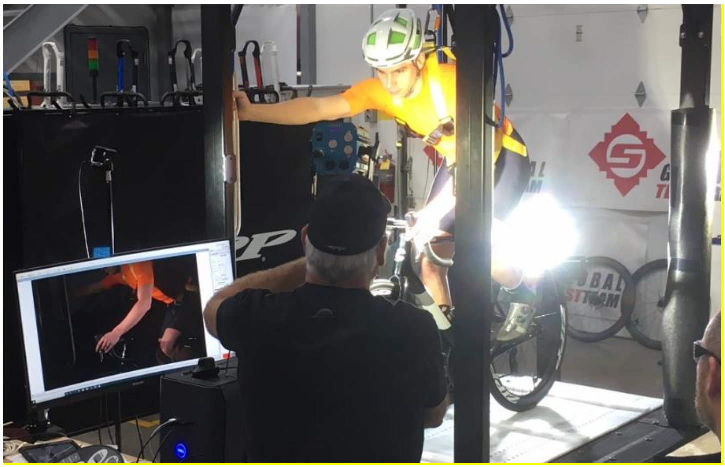


Figure 3 - RollingRoad™, preparing for a test run

The plot below (Figure 4) is one type of dynamic response plot, which can be used as a characterization of surface roughness. An equivalent roughness to the poor-condition asphalt road (shown as a green line) was recreated on the RollingRoad™ to measure the relationship between tire pressure, surface roughness, and system efficiency.

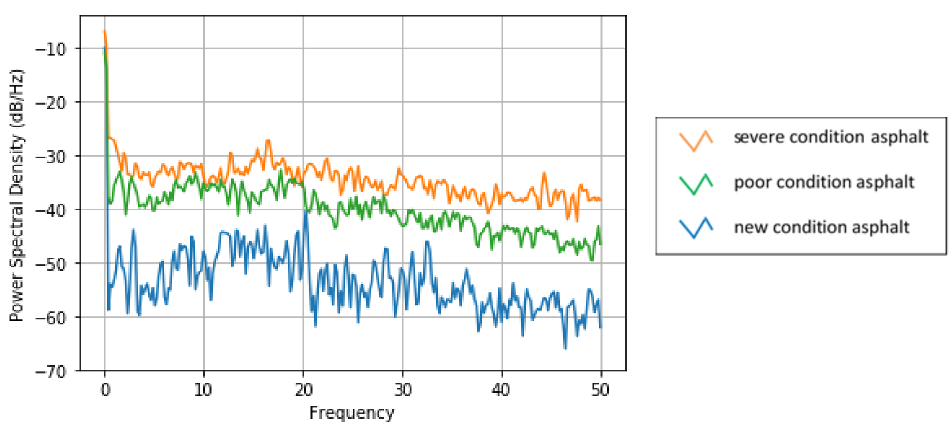


Figure 4 – Real-world cycling dynamic response characterization riding over severe, poor, and new asphalt surfaces in Indianapolis, Indiana

The data represented in Figure 5 below provides good context for why the effects of vibration loss are important to consider when striving to maximize speed on a bicycle. There was a 48 watt decrease in power required between 90 psi (6.12 bar) and 30 psi (2.04 bar). While this graph indicates that tire pressures at or below 30psi (2.04bar) with a 28mm tire are the most efficient over a surface of equivalent roughness, other factors such as tire, wheel, and handling integrity limit the feasibility of using such low pressures. The data is from our RollingRoad™ testing and captures power losses from rolling resistance, vibration loss, and drivetrain while traveling 32kph over a simulated poor-condition asphalt (green line in the dynamic response plot of Figure 4 above).

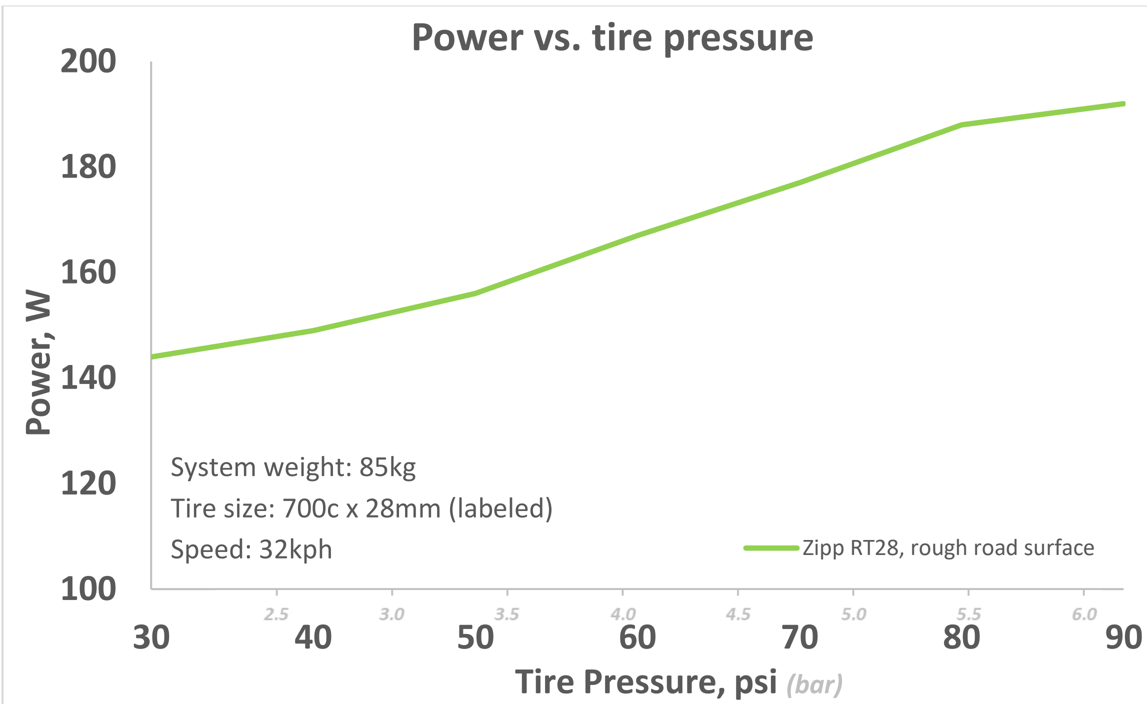


Figure 5 - RollingRoad™ data simulating poor-condition asphalt

"There was a 48 watt decrease in power required between 90 psi and 30 psi."

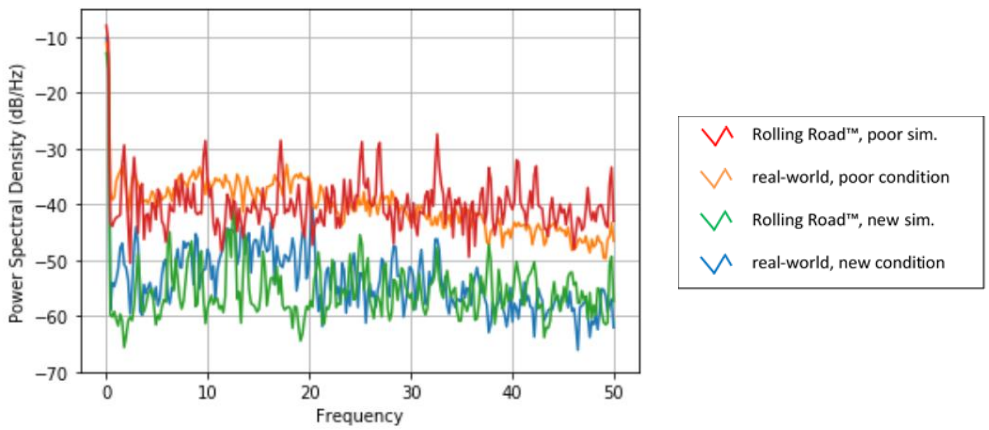


Figure 6 - Cycling dynamic response on RollingRoad™ simulating both new condition asphalt and poor condition asphalt with overlaid real-world dynamic response, illustrating the degree of dynamic similitude between real-world and simulated surface roughness

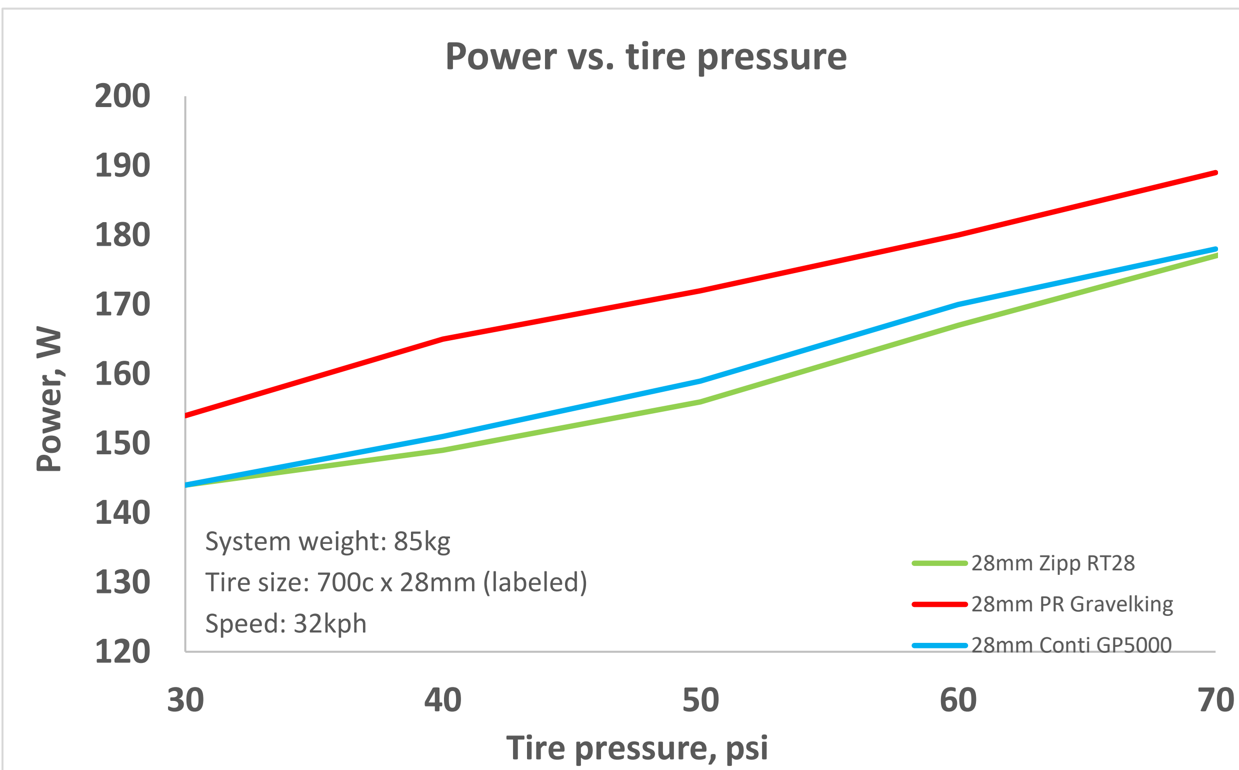


Figure 7 - RollingRoad™ data comparing efficiency of three tire models over simulated poor-condition asphalt

Influences on tire pressure

The new 303 family of wheels allows riders to use much lower pressures than previous wheels. Why? It comes down to how the wheel features affect vertical spring rate in the tire. Vertical spring rate describes the amount of force required to compress the tire a specified distance, typically shown as a ratio of force per distance – e.g. N/mm. It is one of the strongest determinants of ride quality and handling characteristics of a tire.

Three important factors affecting vertical spring rate are discussed here: tire size, tubeless setup, and internal width.

Tire size

In pursuit of maximum speed, we designed the new 303 family of wheels to match perfectly with tires larger than traditional road tire sizes of the past. Larger tires require less pressure, because they have a higher vertical spring rate for a given psi.

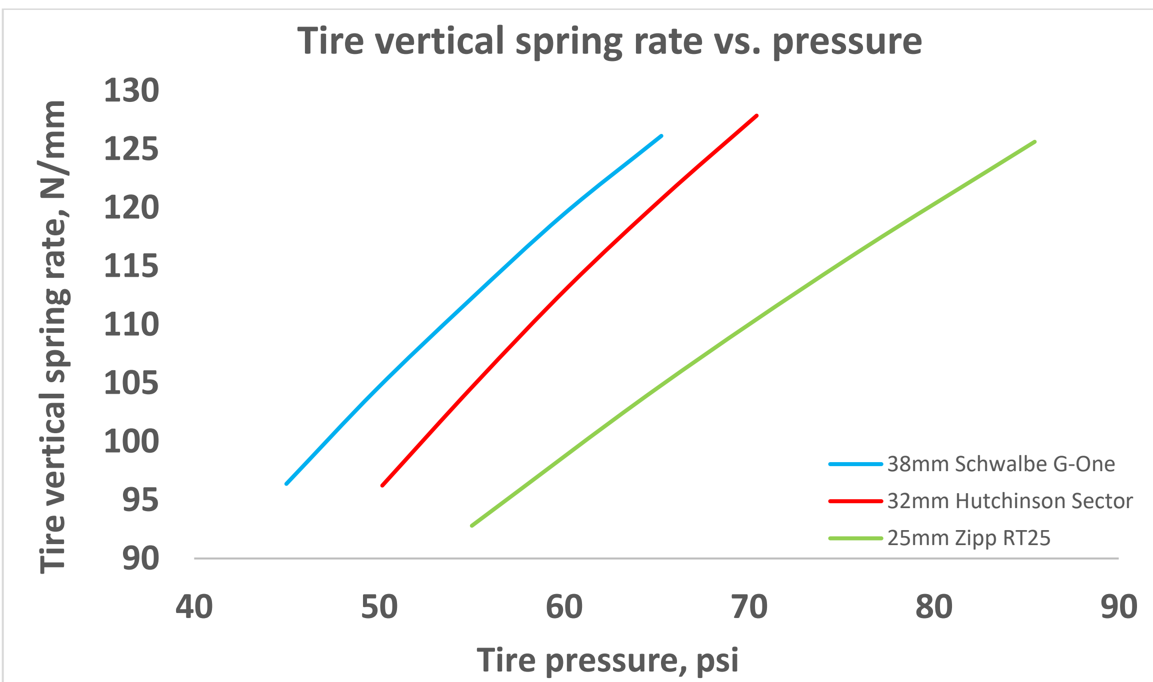


Figure 8 - Tire size affects vertical spring rate at a given tire pressure

Tubeless setup

Inner tubes require pressure to expand and fill the volume inside a tire. When you pressurize a tubeless tire - one which does not have an inner tube - the pressure that otherwise would have been forcing the inner tube to expand is now acting directly on the tire casing. Tubeless tire pressure will need to be reduced to achieve the same vertical spring rate as on a tubed setup. In the case of a 28mm tubeless tire, this means reducing tire pressure by approximately 10psi compared to a standard weight 700x28mm butyl inner tube.

Internal rim width

The internal rim width of our new 303 Firecrest® is almost 20% wider than the previous generation 303. This additional width in the tire bed serves to further increase the tire vertical spring rate by widening the stance of the tire beads, creating a wider tire. As a result, reducing pressure is necessary to achieve an appropriate vertical spring rate for maximum speed.

	Zipp RT25 vertical spring rate, N/mm	
Pressure (psi)	New 303 FC, 25mm TSS	Old 303 FC, 21mm TC
115	156.24	151.95
105	149.50	143.07
95	142.10	134.76
85	133.93	125.64
75	124.41	115.59
65	113.78	104.63
55	101.66	92.80

Figure 9 - A 4mm wider tire bed has similar effect to increasing tire pressure 10psi

"Reducing pressure is necessary to achieve an appropriate vertical spring rate for maximum speed"

Surface roughness, tire rolling resistance, and pressure selection

As surface roughness increases, lowering tire pressure to achieve a lower vertical spring rate will help preserve efficiency by isolating the mass of the cyclist from road inputs, but the optimum tire pressure depends on other factors such as tire rolling resistance. A generalized model is shown in Figure 10 below suggesting how vibration loss and tire rolling resistance combine to define an optimum tire pressure range for a given surface roughness and tire characteristic. Separately, increasing tire size should be considered if crossing below a critical threshold pressure that compromises tire, wheel, and handling integrity. In many cases, these integrity thresholds are the limiting factor determining the lowest feasible tire pressure for achieving maximum speed over rough surfaces.

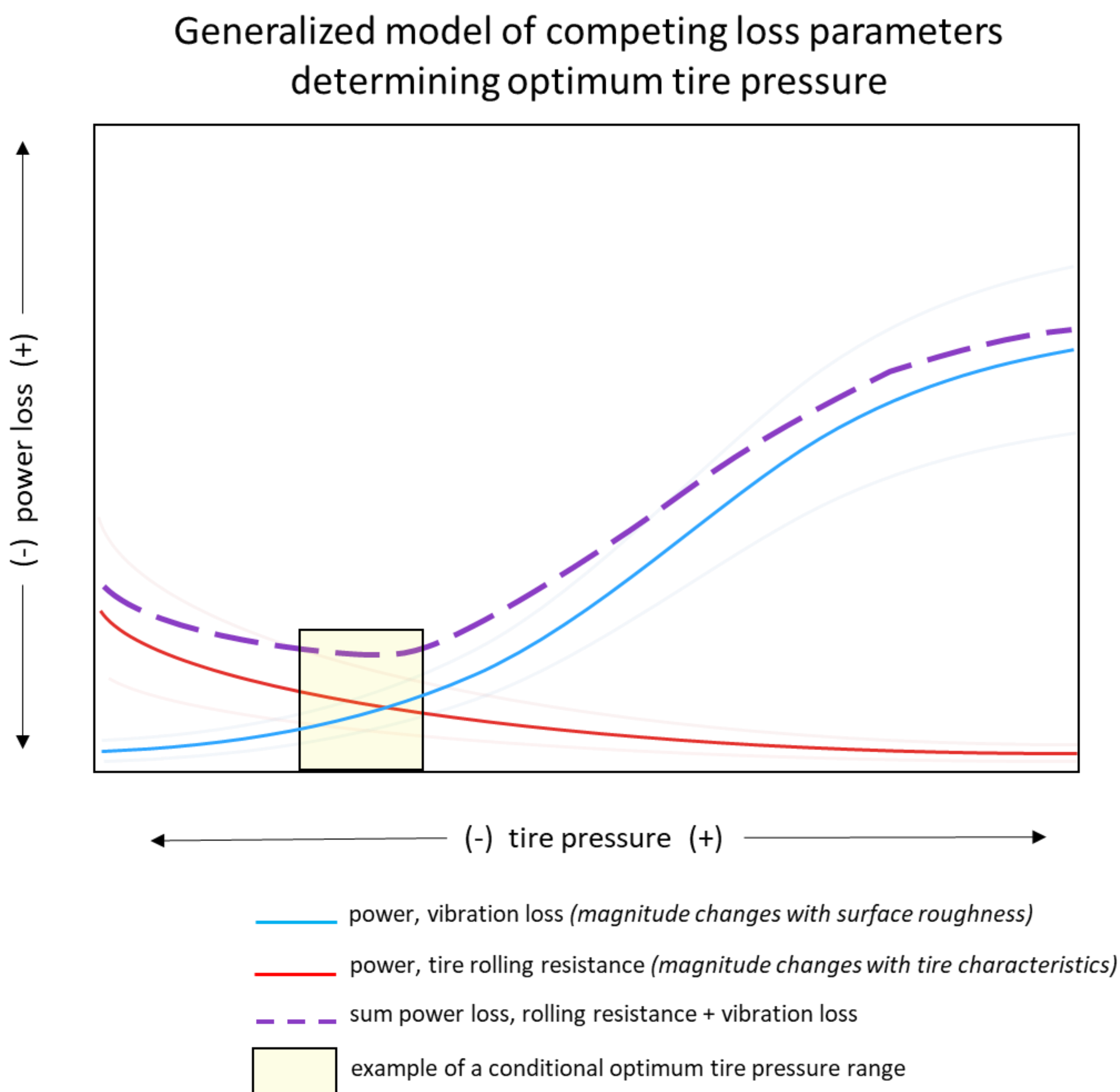


Figure 10

Real world testing

A key premise behind Total System Efficiency™ is the entire system must be considered when making any refinements to one aspect of a wheel. Refining one portion of the system in isolation must be avoided due to dependencies between components of the rider-bicycle system. For this reason, real world testing was employed throughout the 2-year development of the new 303 wheelset family to validate prototype designs and understand the complex interactions between types of efficiency loss.

Real world testing is a critical component to achieving TSE™ in a wheel design because it accounts for nuanced variables that occur while riding a bicycle in the real world, capturing everything that is hard to measure in a lab setting. Real world testing even accounts for factors yet to be identified as relevant.

Conducting real world testing first requires a deep understanding of the underlying physics involved in cycling. In addition, sensors are required to measure many of the terms outlined earlier, such as crank power, bicycle speed, road slope, wind speed, and most recently vibration has been added to the list. If these variables are measured accurately, an understanding can be developed of how different equipment or bicycle setups affect overall efficiency and speed.

Figure 11 - 3rd party wind speed sensor

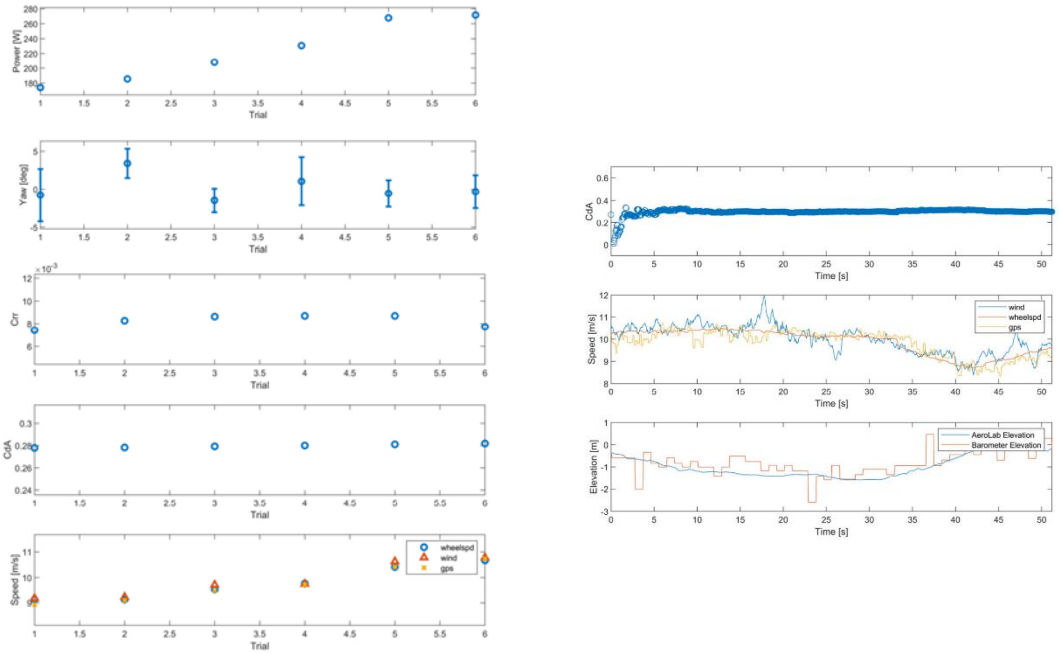


Figure 12 - sample output data from 3rd party testing consultant

With this data we formed conclusions and strategies that lead us to the holistic product design of the new 303 family. The last round of testing in the development of the 303 Firecrest® and 303 S was a validation of the science behind TSE™. Two competitor wheels were compared against the 303 Firecrest® and 303 S wheelsets riding over a dirt road at 35kph. The graph below is showing total power to maintain speed, wrapping up everything into one power number (what you would see on your computer head unit). Similar to the RollingRoad™ data, this graph shows the same trend of lower pressures yielding higher efficiency – or put in more exciting terms – more speed at lower tire pressures!

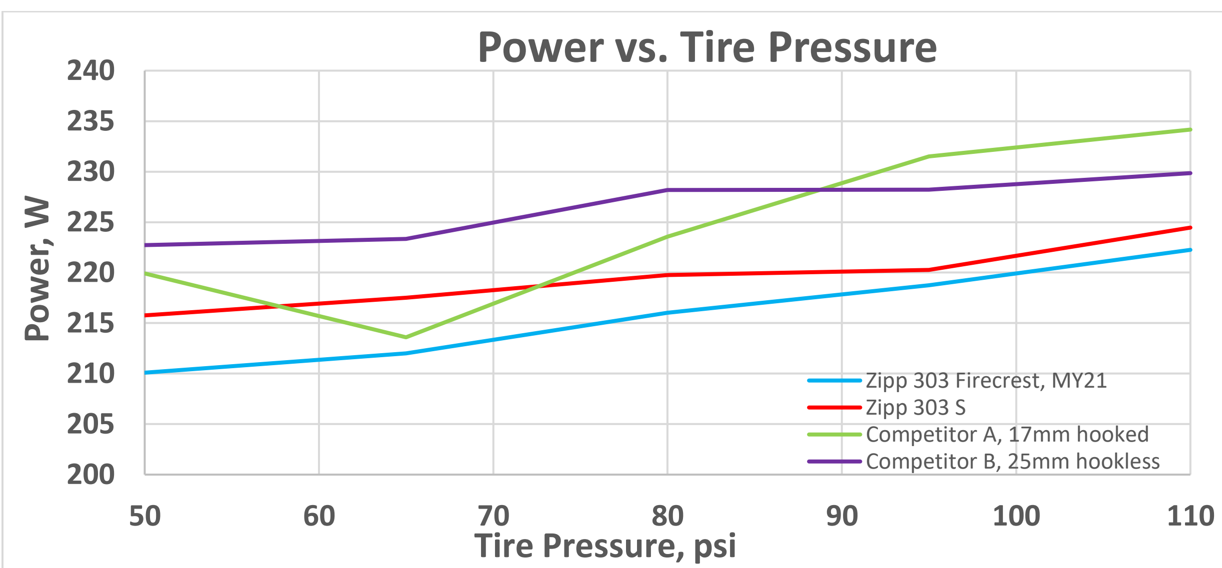


Figure 13 – 85kg rider-bicycle system traveling 35kph using Zipp 28mm tubeless tires at various pressures, data from 3rd party testing consultant. Note: testing system efficiency with pressures above 72.5psi was conducted for scientific purposes. All equipment pressure limitations should be followed.

Summary

Total System Efficiency™ represents a departure from past wheel designs focused on improving a single parameter of a wheel. When focusing on the entire system, small concessions in one aspect of the design can reveal significant improvements in overall efficiency. The combination of a larger tubeless tire, lower tire pressure, a wider rim profile with optimized tire interface, and a compliant rim laminate all work in concert to create a more efficient, faster ride on or off the pavement.

Maximizing the speed of a cyclist is about achieving efficiency of the entire rider-bicycle system. An increase in system efficiency will achieve more speed for the same power input. A key premise behind Total System Efficiency™ is the entire system must be considered when making any refinements to one aspect of a wheel. Refining one portion of the system in isolation must be avoided due to dependencies between components of the rider-bicycle system. Historically, carbon wheel designs have been solely centered around maximum aerodynamic efficiency. Not long ago riders were inflating 19mm tubular tires to 140 psi (9.5 bar) to attain improved aerodynamics at any costs. In many cases this harsh ride likely resulted in a net penalty in speed.

This paper began with a bold claim of 5% increased cycling speed by using wheels designed with TSE™. From the data presented we are able to demonstrate efficiency gains of 24 watts, which translate to an increase in speed from 35kph to 36.75kph (5%) for the same power output.

Pressure Suggestions

For asphalt surfaces, the table below provides starting pressure recommendations for tubeless tires mounted on the new MY21 303 Firecrest®. Visit http://axs.sram.com/tirepressure for an interactive version.

Front/rear PSI recommendations for MY21 303 Firecrest MY21

(rider weight)	(labeled tire width)	
lbs	28	30
99	49/52	45/47
110	50/53	46/48
121	51/54	47/50
132	52/56	48/51
143	53/57	49/52
154	55/58	50/53
165	56/60	51/55
176	57/61	52/56
187	58/62	53/57
198	59/64	54/58
209	60/65	55/60
220	61/66	56/61
231	62/68	57/62
242	63/69	58/63
253	64/70	59/65

** recommendations are a starting point for riders to begin tuning their optimum tire pressure*

Glossary of terms

P_{crank}	power (W) produced by the rider at the crank
c_{loss}	coefficient of drivetrain loss between crank and rear tire contact patch
v_b	speed (m/s) of the bicycle relative to the road
v_w	speed (m/s) of the bicycle relative to the wind, measured in the direction of travel
ρ	air density (kg/m^3)
Cd	coefficient of drag
A	aerodynamic reference area (m^2)
c_{rr}	coefficient of rolling resistance
g	acceleration due to gravity, 9.806m/s^2
θ	incline of road surface (radians)
P_{abs}	power (W) absorbed from vibration of the rider-bicycle system
m	mass of the rider-bicycle system
a	acceleration in the direction of travel of the rider-bicycle system
I	rotational moment of inertia of both wheels
r	radius of the wheel plus tire

References

D. Greenwell, N. Wood, E. Bridge, and R. Add, 1995. *Aerodynamic characteristics of low drag bicycle wheels*. The Aeronautical Journal, Volume 99, Issue 983, pp. 109-120.

S. Gallagher, 2018, April 16. *File analysis: Taylor Phinney at the 2018 Paris-Roubaix.* Training Peaks. https://www.trainingpeaks.com/blog/file-analysis-taylor-phinney-at-the-2018-paris-roubaix/

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