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Rider power curve analysis based on the laws of physical motion circuit

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Abstract: In cycling time trial, the rider must reasonably allocate the energy during the cycling process to achieve good performance. Based on the objective optimization model and sensitivity analysis, this paper firstly analyzes the dynamics of different road conditions during the race; secondly, with the shortest total cycling time as the objective function and the rider's total energy limit, lactate threshold, maximum and minimum speed of cycling as the constraints, an individual time trial objective optimization model is established and the sensitivity analysis is done for both considering the influence of wind speed and wind direction on the rider. The results showed that when the wind direction was in the range of 9-11 rad, it had the least influence on the rider and was favorable to win, and when the wind direction was 7-8 rad and 16-18 rad, it was the most unfavorable to the race result; low wind speed had less influence on the rider, and when the wind speed was greater than 6 m/s, the unfavorable influence on the rider then increased.

1. Introduction

The cycling road time trial event is a specialized cycling event with a long duration and complex routes, which is a major test both for the physical strength and skills of the participating athletes and seawater endurance [1]. The success of the race is related to the type of event, the route and the rider's ability. Each rider generates different power at different times, and different types of riders have different power curves, and according to the rider's power curve and his or her personal ability, it can help the rider plan how to apply power in different sections of the time trial to achieve the best performance. Chen Qiang et al [2] found that fat energy supply decreases and sugar energy supply rises in medium and high load exercise; Wan Hepo et al [3] showed that the mastery criterion about the rhythm during the course of a race mainly refers to the power about an athlete's output heart rate and physical output; Li Hongwei et al [4] showed that athletes ride along the right side of the road for a distance when turning, and then accelerating the turn is beneficial to athletes However, for different types of riders, their power curves are obviously different, and there are few studies on this, so it is urgent to study the power curves of different types of athletes..

In this paper, we firstly established an individual time trial model and obtained the power time curves of different types of riders by solving. Secondly, we considered the influence of weather factors on riders' riding process and performed sensitivity analysis on wind speed and wind direction, and then modified them. Next, we considered the influence of weather factors on riders' riding process and performed sensitivity analysis on wind speed and wind direction, and then modified the model; after that, we compared the model results with the actual situation and performed model testing.

2. Individual time trial model building

As the race progresses and the rider becomes more and more fatigued, i.e., the pedaling frequency of his bike becomes smaller and smaller, the angular acceleration a_ω becomes smaller and smaller, so assuming that a_ω is a decreasing function of t, we have:

$$a_\omega = \ln \frac{yb}{1-ay} = \ln \frac{bt}{1-at} \tag{1}$$

where *a, b* is determined by the type of athlete.

By reviewing the information, the race course consists of straight sections, curves and ramps, then:

①Riders ride in a straight line with no curves or uphill situations;

Angular acceleration of the gear in which the pedal is located:

$$a_\omega(t) = \frac{d\omega}{dt} \tag{2}$$

Then

$$\omega(t) = \int_0^t a_w(t)dt, v(t) = \omega R_1 = R_1 \int_0^t a_w(t)dt \tag{3}$$

where R_1 indicates the radius of the gear connected to the bicycle pedals.

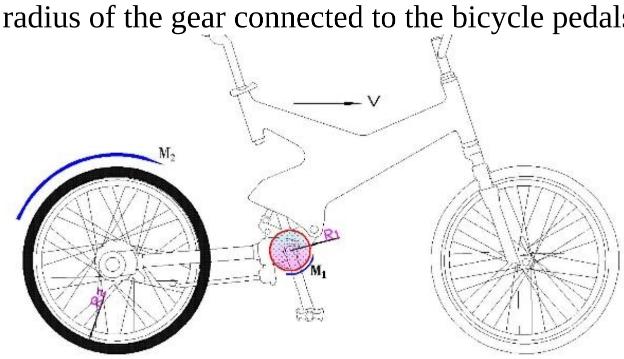

Figure 1 Bicycle moment analysis chart

Suppose that at moment t, the force applied to the pedal by the rider is *F*, and its corresponding moment is M_1, and the resistance moment generated by the air, etc. is M_2. The moment analysis diagram is shown in Figure 1, and by the law of rotation there is:

$$FR_1 - F_f R_2 = Ja_\omega \tag{4}$$

Where the resistance $F_f = \left(\mu mg + \frac{1}{2}\rho s v^2\right)$, $J = \frac{1}{2}MR_2^2$, *M* is the mass of the tire and R_2 is the radius of the tire.

Equation (4) both ends of the same multiplier tire angular velocity ω, $\frac{\omega}{\omega'} = \frac{R_1}{R_2}$, where ω′ denotes the angular speed of rotation of the bicycle gear, then we have

$$F\frac{R_1}{R_2}\omega' R_1-\left(\mu mg+\frac{1}{2}\rho sv^2\right)v=J\omega a_\omega \tag{5}$$

$$\frac{R_1}{R_2}P-f(v)=J\frac{v}{R_2}a_\omega \tag{6}$$

From the above equation it can be seen that *P* is a binary function of *v* and *t*.

$$P=\left[\frac{1}{2}MR_2va_w+f(v)\right]\cdot\frac{R_2}{R_1} \tag{7}$$

Due to the distance $S=\int_0^t v(t)dt$, then time $t=\varphi(s)$, and the course of each rider in the time trial is fixed and uniform, so the distance rider rides can indicate his location, and the distance rider rides in his competition time is the length of the course, then will $t=\varphi(s)$ substituting into equation (7), we have:

$$P(s)=\left\{\frac{1}{2}MR_2v[\varphi(s)]a_\omega[\varphi(s)]+f\{v[\varphi(s)]\}\right\}\cdot\frac{R_2}{R_1} \tag{8}$$

②Rider through the corner situation:

Assuming that the rider turns at a tilt angle of *θ*, the force analysis of the contact point between the tire and the ground, with the gravity of the rider and the bike itself, the downward sloping pressure *F*, and the ground support force F_N, is shown in Figure 2:

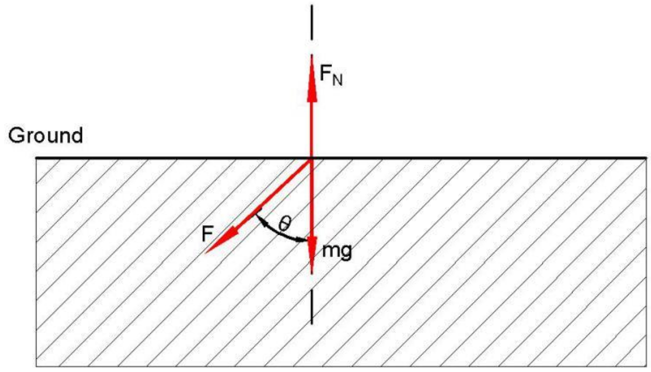

Figure 2 Analysis of the force at the contact point between the tire and the ground during the turn

For the bike and rider, along the track radially by Newton's second law there is:

$$F\cos\theta=\frac{mv^2}{r} \tag{9}$$

Where r denotes the bend radius.

Along the vertical direction by Newton's third law and the hydrostatic conditions are:

$$F\sin\theta+mg=F_N'=F_N \tag{10}$$

At this point, the bicycle is in friction with the ground $f=\mu F_N'=\mu\left(\frac{mv^2}{R}\tan\theta+mg\right)$, then there is:

$$FR_1-\left[\mu\left(\frac{mv^2}{R}\tan\theta+mg\right)+\frac{1}{2}\rho sv^2\right]R_2=\frac{1}{2}MR_2{}^2a_\omega \tag{11}$$

Namely:

$$\frac{R_1}{R_2}P-g(v)=J\frac{v}{R_2}a_\omega \tag{12}$$

The same rider passes through the straight line segment scenario, substituting $t=\psi(s),\quad J=\frac{1}{2}MR_2{}^2$ into the above equation gives:

$$P(s)=\left\{\frac{1}{2}MR_2v[\psi(s)]a_w[\psi(s)]+g\{v[\psi(s)]\}\right\}\cdot\frac{R_2}{R_1} \tag{13}$$

③Riders passing uphill.

Let the total mass of the bicycle and rider be m, the speed when going up the slope is V, the traction force generated by the rider is F. The resistance term changes when going up the slope, in addition to ground friction and air resistance, increasing the resistance to going up the slope, as the height of different slopes is different, then the slope angle is different, so let the foot of the slope be α. The force analysis diagram is shown in Figure 3.

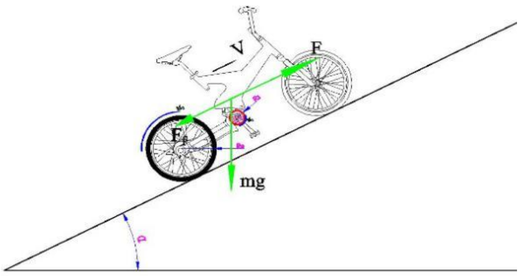

Figure 3 Force analysis after an uphill section

From Newton's second law and the hydrostatic conditions it follows that

$$FR_1-\left(\mu mg\cos\alpha+mg\sin\alpha+\frac{1}{2}\rho sv^2\right)\cdot R_2=Ja_\omega \tag{14}$$

$$\frac{R_1}{R_2}P-\xi(v)=J\frac{v}{R_2}a_\omega \tag{15}$$

Similarly substituting $t=\varepsilon(s),\quad J=\frac{1}{2}MR_2^2$ into the above equation gives

$$P(s)=\left\{\frac{1}{2}MR_2v[\varepsilon(s)]a_\omega[\varepsilon(s)]+\xi\{v[\varepsilon(s)]\}\right\}\cdot\frac{R_2}{R_1} \tag{16}$$

The rider's total energy during the race should be less than a certain limit, i.e.

$$\int_0^L P(s)ds\le E_{\text{give}} \tag{17}$$

The rider should try to avoid the production of lactic acid in the body during the ride and, in order to achieve better results, should ride at a power greater than the minimum of the average power of similar riders over the years, i.e.

$$P_{\min} \le P(s) \le P_{\max} \tag{18}$$

Correspondingly there should be a speed limit for riding, viz:

$$V_{\min} \le 1 \le V_{\max} \tag{19}$$

In summary, the objective function and constraints are established:

$$\min T = \begin{cases} \left\{ \frac{1}{2} MR_2 v[\varphi(s)] a_{\omega}[\varphi(s)] + f\{v[\varphi(s)]\} \right\} \cdot \frac{R_2}{R_1}, \text{ Straight line driving} \\ \left\{ \frac{1}{2} MR_2 v[\psi(s)] a_{w}[\psi(s)] + g\{v[\psi(s)]\} \right\} \cdot \frac{R_2}{R_1}, \text{ Curve driving} \\ \left\{ \frac{1}{2} MR_2 v[\varepsilon(s)] a_{\omega}[\varepsilon(s)] + \xi\{v[\varepsilon(s)]\} \right\} \cdot \frac{R_2}{R_1}, \text{ Uphill driving} \end{cases} \tag{20}$$

$$\text{s.t.} \begin{cases} \int_0^L P(s)ds \le E_{\text{give}} \\ P_{\min} \le P(s) \le P_{\max} \\ v_{\min} \le v \le v_{\max} \end{cases} \tag{21}$$

3. Analysis of results and discussion

3.1 Individual Time Trial Model Application

The time trial for the 2021 Olympic Games in Tokyo, Japan, was held in Mount Fuji, Japan, and the women's group was required to ride one lap along the track, and the men's track was twice as long as the women's track, and we considered the less curved sections of the track as straight sections and the more curved sections as curves, and the statistics showed that there were 19 curves and 6 ramps in the women's individual time trial, and firstly, the model was solved to derive the power curve for professional female athletes in the time trial. According to the literature, the absolute average power of male athletes is 27 % higher than that of female athletes, and the relative average power is 13 % higher [5], according to which the power curve of female athletes is modified considering the gender of riders, so as to obtain the power curve of male riders. As shown in Figure 4:

Figure 4 2021 Tokyo Olympic Games Time Trial Course Map

Substituting each parameter of the Tokyo 2021 Olympic track into the model to solve, the relationship between the position of the riders of different genders on the track and the applied force at the minimum time was obtained as shown in the Figure:

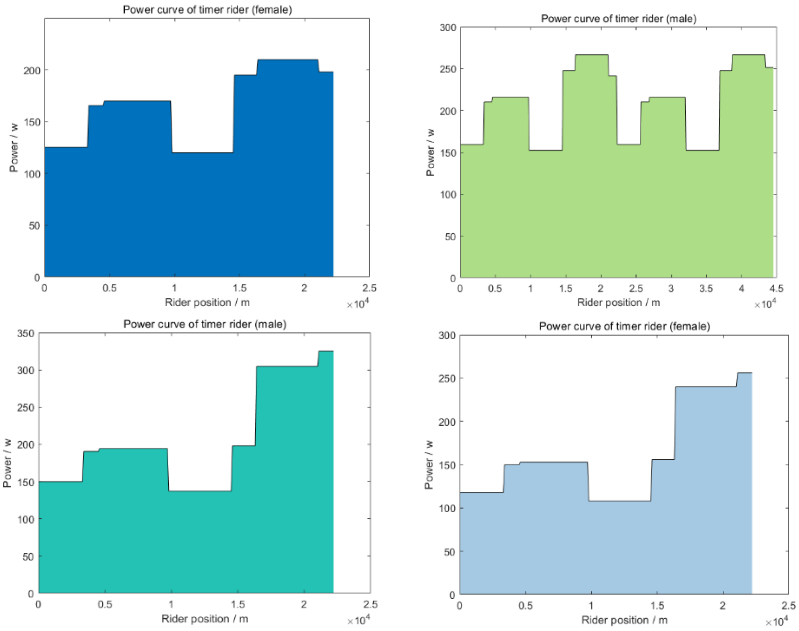

Figure 5 2021 Tokyo Olympic Games Male and Female Athletes Power Curve

From Figure 5, we can see that the power curves of the men and women's time trials are roughly the same, but the men's power curve fluctuates more because the men's course is twice as long as the women's course, i.e. the same place needs to be passed twice, and if we separate the men's power curve from the middle, the fluctuation is comparable to the women's riders.

3.2 Sensitivity analysis of the model to the environment

The environmental factors during the cycling road race have potential effects on the riders' race results, especially the wind strength and wind direction factors, so we develop the sensitivity analysis of the model to the environment based on the model established in Problem 1, using the wind strength and wind direction as an example.

Taking the rider's situation when passing through the curve as an example, the force analysis is as follows (Figure 6):

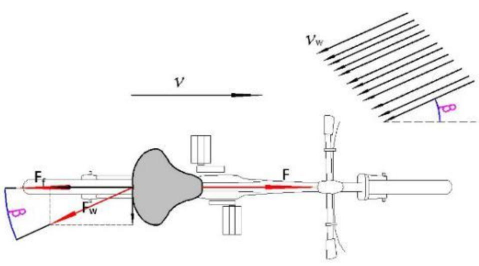

Figure 6 Force analysis diagram considering wind strength and wind direction

Where V_w is the wind speed, β is the angle between the wind speed and the rider's riding speed, V is the rider's riding speed, F_f and F_w are the resistance and wind force on the rider's riding process respectively, and F is the traction force generated by the rider.

Then by the law of rotation we have:

$$FR_1 - \left[\mu\left(\frac{mv^2}{R}\tan\theta + mg\right) + \frac{1}{2}\rho s\left(v - v_w\cos\beta\right)^2\right]R_2 = \frac{1}{2}MR_2^2 a_w \tag{22}$$

Namely:

$$\frac{R_1}{R_2}P - z\left(v - v_w\cos\beta\right) = J\,\frac{v - v_w\cos\beta}{R_2}a_\omega \tag{23}$$

Substituting , $t = \zeta(s)$, $J = \frac{1}{2}MR_2^2$ into the above equation yields:

$$P(s) = \left\{\frac{1}{2}MR_2 v[\zeta(s)]a_w[\zeta(s)] + z\{v[\zeta(s)]\}\right\}\cdot\frac{R_2}{R_1} \tag{24}$$

①Sensitivity analysis of the model to wind strength

When the wind speed varies continuously between the common 1-7 m/s, thus performing a sensitivity analysis, the results obtained using MATLAB are shown in Figure 7:

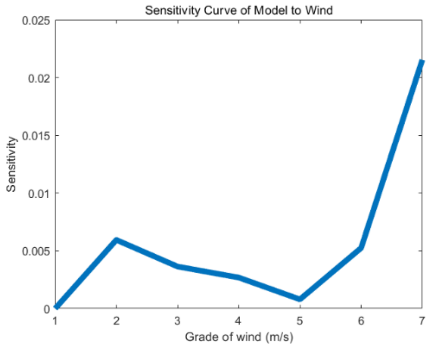

Figure 7 Model sensitivity curve to wind strength

②Sensitivity analysis of the model to wind direction

When the wind direction is continuously changed between 0-20 rad, thus performing a sensitivity analysis, the results are obtained using MATLAB as shown in Figure 8:

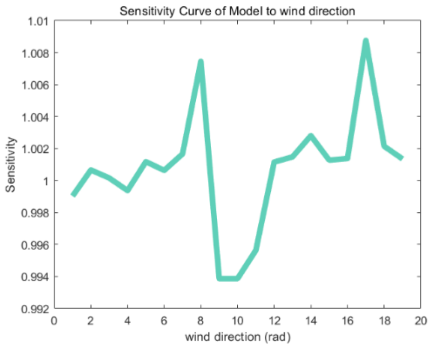

Figure 8 Model sensitivity curve to wind direction

In Figure 7, when the wind is less than 6 m/s, the model is less sensitive to the change of the wind strength parameter; when the wind strength is greater than 6 m/s, the model is more sensitive to the wind strength, and the increase of wind strength will have a greater impact on the results. It can be seen in Figure 8 that the model is most sensitive to the wind direction when the wind direction is 8 rad and 17 rad; when the wind direction is between 9-11 rad, the wind direction has the least effect on the model, so the time trial competitors in the actual race process, in the case of low wind strength, the wind strength has little effect on the riders' race results, but the wind direction has a greater effect on the results, and the wind direction of 7-11 rad has the wind direction of 7-11 rad is the most favorable to the race result.

4. Conclusion

In this paper, a model applicable to any type of athlete was developed using theories such as optimization models and sensitivity analysis to determine the relationship between their position on the course and the applied power collected for the 2021 Tokyo Olympics, and then environmental factors such as wind strength and direction during the race. The model was also modified for environmental factors such as wind strength, wind direction, and rider deviation from target power during the race, and finally the developed individual time trial model was extended to the team time trial to derive how team athletes should apply power in the race to achieve the best performance, and the model effectively achieved the initial stated goal.

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