Optimizing Performance at the Unique Dick Lane Velodrome

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Introduction - Disclaimer

Two Audiences
– Researchers
– Cyclists
Purpose
– Concept of the model
– Discuss what can be learned
– Handout

• This topic was NOT part of my dissertation but shows how a “side project” can get out of hand. I believe this side project was involved enough to be a “2nd dissertation”.
• My dissertation was on biomechanics and motor control of cycling in amputees.
• Tim and I did this project because we’re geeks that love cycling.
• This presentation was put together because we know you’re a geek too and we thought you’d be interested.

Introduction
• The Model
• Increasing Performance
• Pacing Strategies
• Why is Dick Lane slow?

• Disclaimer – To researchers and hardcore engineers reading/watching this, the presentation is intended for a more general audience. Therefore, some topics will be glossed over, detail removed and you’ll even see free body diagrams missing some forces. This was done intentionally. The purpose of this presentation is to explain the concepts behind the model, NOT how to build the model.
• If you recognize the technical details I left out, then you know what is supposed to be and I don’t have to tell you.
• To a general audience, there will still be math equations…
• Also, the units were changed to what this audience is used to, thus mph and not kph or m/s
Introduction

- Pursuit Model
  - Cyclist physiology
  - Aerodynamics
  - Rolling resistance
  - Track Geometry
  - Fatigue
  - Gear selection
  Martin, et. al., 2006, Med Sci Sports Exerc

- The model takes into account all of this stuff.
- The model is an incremental improvement on several prior models made by people smarter than we are.
- Our contribution is “improving” the two main models, putting them together, adding in a fatigue function and gear selection. Then getting the whole mess to work.
- References:
  - Extra note: The model presented in Martin et al., 2006 is an evolution of another model:
  - Extra extra note: the model owes a lot to Newton and everyone in between, so in effect we’re all just “standing on the shoulders of giants.”

Forces on the bike/ rider

- Aerodynamic Drag
- Gravity
- Energy to Accelerate
- Rolling Resistance
- Drivetrain Resistance

Pursuit Model

- The model uses a concept called forward integration that allows the model to predict velocity and changes in velocity with power. In effect, it allows for non-steady state cycling such as the standing start of a pursuit
- This is an example of one of the thousands of calculations the model has to do.
- The model knows where the rider is on the track and how fast he’s going at a known time point

Forward Integration

1st Time point
30 mph, 50m past Pursuit line
The cyclist is producing power and the power curve was calculated using the de Konning model.

The de Konning model allows the model to generate a power output curve for a cyclist given some physiological measurements. We rearranged this model to use a whole slew of field derived measurements. Our modified de Konning model would then feed power data into a forward integrated model by Martin et al., 2006.

The field/lab derived measurements include a protocol described by Hunter & Coggan, 2010 to get power output over 5 sec, 1 min, 5 min, 20 min. On a separate day the cyclist performed a 1 min isokinetic maximal output test from a standing start in the laboratory to quantify the amount in the cyclist’s “anaerobic fuel tank”. This is basically a kilo.

Power output of the cyclist is then resolved as the propulsive force on this diagram (There are several intermediate steps I just glossed over but if you’ve realized that then you know what those steps are.)

The two main forces the rider must overcome in this diagram are related to aerodynamics and rolling resistance.

Note, rolling resistance is related to the Normal force. This force is not always the weight of the bike/rider but increases in the corners.

All of these forces act about the center of mass (COM) of the bicycle/rider. This is represented by the yellow circle.

Note, changes in potential and kinetic energy will be discussed later.

In this case, the propulsive force is greater than the resistance forces and so the rider will accelerate.

The Martin model was used to calculate the final velocity of the rider after 0.1 seconds.

Note - We created an additional section in the model to better locate the COM based on the geometry of the bike, the rider, and the position of the rider on the bike. The mass of the rider’s limb segments are calculated based on Zatsiorsky et al., 1990. COM of the bike was measured.
The result of the last calculation becomes the baseline for the next time point, the calculation is repeated. Hence, forward integration. In the middle of all of this, fatigue is accounted for.

- Cyclists cannot produce the same amount of power (or torque as shown in this graph) over 5sec as one can over 20 minutes.
- The model takes a torque time curve generated from laboratory testing, takes the first derivative and uses that as the rate of torque decay (fatigue) during the model run.
- Remember, power is crank torque times cadence times a constant. Thus, if you maintain power and change cadence, you change torque.
- The power of the cyclist is divided by the cadence (related to gear selection) to find the torque.
- The torque is then used to look up where the cyclists is operating on the fatigue curve. The rate of fatigue is then used to determine how much to reduce crank torque for the next data point. Thus the harder you go, early in the pursuit, the more you “pay” for it later. Also, the more you “fall off the gear”, the more you “pay”.

The center of mass of the bike/rider moves when the cyclist goes throughh the corners.
- The lean angle is related to velocity and radius of the corner. Lean angle will increase as velocity increases or the corner gets tighter.
- As the cyclist leans into the corner, COM falls and moves inside the corner.
- The horizontal force is related to the centripetal acceleration of the COM. This force will increase with velocity or as the corner gets tighter. Note, the radius used in the radius of the corner minus the horizontal movement of the COM.
- The normal force used to calculate the rolling resistance and is the square root of the bike rider weight \((mg)^2\) plus the horizontal force^2.
- As the normal force increases, so does rolling resistance.

If power stays constant
- When you lean into the corner, COM falls, resulting in a change in potential energy that increases kinetic energy of the bike/rider so the rider speeds up.
• Through the corner, forces related to centripetal acceleration about the COM increase. The normal force increases and so the rolling resistance increases. Velocity goes down.

• Exiting the corner is the reverse of entering the corner. COM goes up, velocity goes down.

• This is modeled output of a 250m wooden track where the cyclists holds 800 watts for the whole lap.
• It starts on the front-stretch pursuit line.
• Velocity increases as the cyclist leans and enters turn one.
• Through turn 1 & 2, velocity is slowly “bled off” because
  • Normal force increased, thus rolling resistance
  • The velocity increased, thus power to overcome drag, power is held constant so the aerodynamic forces will bring speed back down
• The exit of turn 2 results in a decrease velocity as the rider becomes more upright.
• Down the backstretch, velocity increases because aerodynamic forces are reduced due to the decrease in velocity.
• The green line represents the average speed for the lap.
• The red line represents the average speed IF there were no corners at all. This allows you to see the “cost” of a velodrome’s geometry.
The physics side of the model was calibrated using a power tap hub on loan from our buddy, Pete Antonvich. This allowed for power and velocity to be recorded at the same time during a 2k pursuit.

This graph shows the field data (pink line) and the model prediction (blue line) for the first minute.

Note the speed is in kph and the graph is “zoomed in” to show how well the model predicts speed.

I think this is really neat. Personally, I never expect mathematical models to predict “real world” results.

From here on out, we’re going to talk about model results. These are the “baseline” conditions use to compare against.

DLV – Dick Lane Velodrome

Male Cyclist (me)

Physical and physiologic testing done around July 2010

CDA = .280

5 sec W/kg = 16.6

1 min W/kg = 8.4

5 min W/kg = 5.2

Functional Threshold = 4 W/kg

“Optimally Paced”

Peak power = 825 Watts

Transition to constant power = 15 seconds

Constant Power = 444 watts

“Standard day” (air density = 1.23 kg/m³)

4:12.3 – this time is in not the fastest but faster than average of historical times at DLV (mean – 4:25.6, std. dev = 15.8 sec)

Note – During a 4k event in August 2010, my 3k split, corrected for weather conditions was 4:14 so the model is pretty good.

Aerodynamic drag constitutes 92% of the power requirement for 30 mph at a wooden track and 77% for DLV. Why that is, will be discussed later.

The point here is aerodynamics matter.

Thus a great way to improve performance would be;

- Reduce aerodynamic drag
- Increase power

Aerodynamic Drag

- Aerodynamic Drag (30 mph)
  - 92%*
  - 77%**

* Wood velodrome ** Dick Lane velodrome
Aerodynamics of Cycling

\[ P_{\text{aero}} = \frac{1}{2} \rho \ CDA \ V_a^2 \ V_g \]

- \( \rho \) = Air Density
- \( CDA \) = Drag Coefficient \* Area
- \( V_a \) = Airspeed
- \( V_g \) = Groundspeed

Here’s the basic equation to calculate the power requirements to overcome aerodynamic drag.

- \( \rho \) = Air Density
  - Kg/m³
- \( CDA \) = Drag Coefficient \* Area
  - We will discuss this as the combination of the drag coefficient and the frontal area of the cyclist.
- \( V_a \) = Airspeed
  - Velocity of the air relative to the cyclist
  - Note, this gets squared and would change with wind conditions
- \( V_g \) = Groundspeed
  - Velocity of the cyclist relative to the ground. This is was the cyclocomputer reads.

A major assumption in this current model is:
- THERE IS NO WIND

Therefore, \( V_a = V_g \) and so we look at things at \( V_g^3 \)

The no wind assumption will be discussed at the very end.

A simple (read has lots of assumptions) wind model was used at the end to “correct” for wind.

We’re working on a way to model wind conditions around a velodrome.

Air Density

- Altitude
- Weather Conditions

Air density matters for performance.

You can’t control it but its good to know its effect.
Air Density

- Altitude $\uparrow$
- Temperature $\uparrow$
- Humidity $\uparrow$

$\text{Air Density} \downarrow$

$N_2 = 28$, $O_2 = 32$, $H_2O = 18$

- WHAT?! Air density decreases with increasing humidity? But the air is so “thick” outside.
- Air is made up of mostly Nitrogen ($N_2$) and Oxygen ($O_2$)
- $N_2$ has a molecular weight of 28
- $O_2$ has a molecular weight of 32
- $H_2O$ has a molecular weight of only 18
- Therefore, the more you displace the “heavy” $N_2$ and $O_2$ with the “light” $H_2O$, the less mass per volume and the less density.
- Air may feel “thick” to you but its actually thinner.
- Humid air does not transfer heat as well and that may be one reason why it feels thick but the heat transfer properties of humid air will not affect cycling performance during a 3k.

Air Density

- This is the effect of humidity on 3k times.
- The y-axis is time saved over a 3k so a positive number is good.

Money = Speed; How fast do you want to go?

- We’re going to talk about better ways to spend your money to increase performance.
- Much of this section is based on data presented in the article;
- Because we used a lot of data presented in this article, the “baseline” CDA was changed to .269 and the fatigue function in the model was turned “off”.
- Trivial note, this is the race car I worked on during my time in pro-drag racing. We spent a bunch of money and only went marginally faster.
The cost of going faster

**Internal factors**
- Interval training
- Altitude training
  - “Sleep high, race low”
- Caffeine
- Doping
  - EPO or blood doping

**External factors**
- Shoe Covers
- Aero helmet
- Aero wheels
- Aero frameset
- Aerobars
- Wind tunnel
- Gruber Motor
  - “Mechanical Doping”

One way to go faster is through “internal factors” that would increase the cyclist’s ability to produce more power.
- Interval training (Jeukendrup & Martin, 2001)
  - Power increase of 5%
  - Cost assumed to be one month of coaching at $200/month
- Altitude training (Jeukendrup & Martin, 2001)
  - Power increase of 2%
  - Cost for an altitude tent = $2400
- Caffeine (Jeukendrup & Martin, 2001)
  - Power increase of 5% with 400 mg an hour before competition
  - Cost = $4.50 at Starbucks
- Doping (Eichner, 2007)
  - EPO
  - Power increase of 6% for one month regimen
  - Cost of EPO treatment for renal failure = $5000 per year
  - Assumed cost = $5000/12 or $417

Another way to go faster is to reduce aerodynamic drag
- Shoe Covers (adjusted from data in Kyle, 2003)
  - Reduction of ~150 grams in drag savings
  - Converts to a CDA reduction of 0.0073 m²
  - Cost = $30.00
- Aero helmet (adapted from Sidelko, 2007)
  - Reduces power requirement by 3.8%
  - Cost = $140.00
- Aero wheels compared to std. rim, 36 round spokes (Kyle, 2003)
  - HED jet 9 used for aero front wheel (data from HED website)
    - CDA reduction of 0.0056 m²
    - Cost = $900
  - Carbon flat disc used for rear wheel
    - CDA reduction of 0.0068 m²
    - However, the rear wheel is blocked by the frame and is adjusted by 0.5 to compensate (Jeukendrup & Martin, 2001)
    - Cost = $1100

Aero frameset compared to round, steel tube bike
- Assumed to be Felt and similar drag reduction to a Cervelo or Lotus (Jeukendrup & Martin, 2001)
  - CDA reduced 0.020 m²
  - Cost = $4440

Aerobars
- The modeled rider was already in an “aero” position so CDA was increased to 0.307 m² (Jeukendrup & Martin, 2001)
  - Cost = $180

Wind tunnel
- “Optimizing” position in a wind tunnel should reduce CDA by 0.029 m² (Jeukendrup & Martin, 2001)
  - Cost = $1000 for 2 hours in the A2 tunnel plus travel to NC

Gruber Motor
- This is the Motor assist system Cancellara was accused of using.
  - Claims increase in 130 watts, I used 130 watts in the model but my feeling is the actual benefit may be less.
  - Cost = $2400
The cost of going faster

<table>
<thead>
<tr>
<th>Item</th>
<th>Seconds saved in 3k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Everything</td>
<td>30.8</td>
</tr>
<tr>
<td>Gruber Motor</td>
<td>24.1</td>
</tr>
<tr>
<td>Wind Tunnel</td>
<td>18.2</td>
</tr>
<tr>
<td>Caffeine and Training</td>
<td>11</td>
</tr>
<tr>
<td>Aerobars</td>
<td>10.1</td>
</tr>
<tr>
<td>Caffeine</td>
<td>7.6</td>
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<tr>
<td>Interval Training</td>
<td>6.2</td>
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<tr>
<td>EPO</td>
<td>6.1</td>
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<td>Altitude</td>
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<tr>
<td>Aero Helmet</td>
<td>2.9</td>
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<tr>
<td>Skinsuit</td>
<td>2.7</td>
</tr>
<tr>
<td>Aero/Disc Wheelset</td>
<td>2.6</td>
</tr>
<tr>
<td>Altitude Tent</td>
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<tr>
<td>Shoe Covers</td>
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<tr>
<td>Aerobars Front Wheel</td>
<td>1.5</td>
</tr>
<tr>
<td>Disc Rear Wheel</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Note – If simply summed, everything would be a 53 second time savings

The cost of Everything is ~$11,000

- You can’t simply add the seconds saved because things interact.
- The item “everything” represents what would happen if you combined everything in the red box.
- If you simply added everything, you’d “save” 53 seconds. Yet when you adjust for everything in the model, it calculates a time savings of 30.8 seconds. This is due to how all the variables interact within the model.

- Just because the wind tunnel may shave 18.2 seconds, it does cost $1000 for the service. For those of us on a budget, it may be a good idea to look at things from a cost/benefit perspective or $ spent per second saved. Low number = good

<table>
<thead>
<tr>
<th>Item</th>
<th>$/sec saved in 3k Pursuit</th>
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</thead>
<tbody>
<tr>
<td>Caffeine</td>
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<td>Shoe Covers</td>
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<td>Aerobars</td>
<td>17.82</td>
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<tr>
<td>Caffeine and Training</td>
<td>18.19</td>
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<tr>
<td>Interval Training</td>
<td>18.24</td>
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<tr>
<td>Aero Helmet</td>
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<td>Skinsuit</td>
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<td>Wind Tunnel</td>
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<td>Gruber Motor</td>
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<td>Everything</td>
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<td>EPO</td>
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<td>Altitude Tent</td>
<td>1044.9</td>
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<tr>
<td>Disc Rear Wheel</td>
<td>1222.2</td>
</tr>
</tbody>
</table>
Pacing the Individual Pursuit

- Pacing the pursuit will also effect times.
- The fatigue function in the model in combination with the modified de Konning model allows us to explore the effect of pacing on pursuit performance.

Pacing Strategy

- The red area represents anaerobic energy used and how it is distributed over the pursuit.
- The blue area represents aerobic energy. Notice it takes a while for it to come on. The model assumes the rider will always try to operate at max aerobic capacity. Thus it distributes anaerobic energy to determine output of the cyclist.
- The modeler determines how high the peak torque will be and the time to constant energy.
- Granted, it not realistic to tell the athlete, put out a peak torque of X and a time to constant energy of Y but the model does provide split times the athlete will need to hit if he/she does this pacing strategy.
- The time at peak torque is determined by a formula that includes the inertial properties of the wheel/bicycle system as well as the cyclist’s mass and a bunch of other complicated stuff. I’m just going to leave it at that for now.

From there, the model produces an “ideal” cadence curve. Basically, it has physiology data from the cyclist that relate cadence to crank torque so it pulls that information in. It applies that curve to the torque curve and it gives us the predicted ideal power output of the cyclist. These cadence models are based on data from the 5 sec, 1 min, 5 min, 20 min laboratory time trials.

The combination of the predicted torque curve and ideal cadence curves produces a power curve that keeps peak power at the setting provided by the modeler and based on laboratory data.

In addition, the “amount” and anaerobic energy available in the cyclist’s “gas tank” was determined by doing a brutal 1 min standing start laboratory time trial on a computer controlled cycle ergometer. The aerobic component in the crank torque was subtracted from the output. The curve was then integrated to determine the amount of energy used in Joules. This technique is similar to the method described in de Konning et al., 1999. The amount of anaerobic energy available to this cyclist was 20277 Joules.

A kilo would be a great field test to derive this and it would be interesting to see what the difference was between endurance and sprint trained cyclists. If enough data was collected, you could probably develop tables to assume anaerobic energy and the model would be much simpler to apply in the real world.
So once you have the power curve, the model then predicts velocity as can be seen here. The “humps” in the curve are related to the infamous hill on the Dick Lane Velodrome.

Actual crank torque is then calculated based on the velocity of the bike and the gear selected. Remember power is torque times cadence so as speed decreases and power stays the same, torque increases.

The effect of the hill can be seen by “waves” in the torque curve from about 30 seconds on.

In this model, fatigue is related to crank torque. So fatigue for each 0.1 seconds is calculated.

The ideal power output of the rider is adjusted for fatigue at the next time point.

This curve shows how the ideal power output of the cyclists is adjusted as the pursuit begins.

The y-axis is a percent of ideal power. So after about 20 seconds this cyclists can only produce about 94% of his ideal or fatigue free power.

This fatigue function essentially penalizes the rider later in the pursuit for going out harder in the beginning.
• If you do this for a combination of peak power and time to constant energy conditions you get this neat looking graph.
• The blue “valley” represents the optimal pacing strategy.
• This suggests optimal pacing for a 3k is not to go out too hard too soon (haven’t we heard that before!)
• It also says if you do go too hard at the beginning, you can “save” the pursuit by quickly coming off the gas and dropping down to constant output.

• Pacing Strategy

• So what about the kilo?
• KILL IT, DON’T LOOK BACK, JUST GO!!!!!
• THERE IS NO PACING FOR THE KILO!
• Hmm… Haven’t heard that before too?

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The Unique
FOR ALL YOUR RIDER AND SPECTATOR INFO
Introduction

Our beloved and unique Dick Lane Velodrome includes a stream and a tree in the infield.

It was also built as a 1/5 oval in the '70s by folks that didn’t know how to build a velodrome but did know sidewalks. So it was built as a series of sidewalk “panels”

The velodrome also has tight corners and long straights

Underneath this nice new coat of paint is a very rough and bumpy surface.

Coefficient of Friction

- DLV = 0.0098
- T-Town = 0.004
- 250 Wood = 0.0025

Rolling resistance can be calculated by methods outlined in Martin et al., 2006.

This was done and the DLV has a very high coefficient of friction compared to other velodromes.

T-Town is the an outdoor concrete velodrome in Trexlertown, PA. It is known for its wide corners.

I found dimensions for a 250m wooden track on the internet one day but I forgot to write down the reference and where it is. I believe it is the Adelaide Superdrome. It has wider corners than DLV but tighter corners than T-Town. Today we’ll assume this is similar to the LA velodrome.

The rolling resistance for concrete http://sportsci.org/2006/jcm.htm and wooden veldrome may be found in Martin et al., 2006

Tim and I brought out some fancy laser survey equipment and completed a survey of the black line.

This is the change in elevation for one lap of the DLV. The difference between is 1.066 m or about 42 inches

This is the infamous hill on our velodrome.
Purpose

• What is the “cost” of the hill?
• Rolling resistance and corners?
• Compare DLV to:
  • T-Town
  • 250 wooden track

The Hill

3k Times

• With hill = 4:13.4
• W/o hill = 4:12.8

The equation

\[ P E_{dr} = \frac{1}{2} \rho CDA V^3 + \mu V F_n + \Delta PE/\Delta t + \Delta KE/\Delta t \]

Coefficient of Friction

- The effect of the hill is actually pretty minimal at 0.6 seconds.
- Some of this is due to the aerodynamic drag varying with the cube of the velocity and some due to the extra fatigue induced every time the cyclist “climbs” the hill and reduces cadence (torque increases).

- This is a more complete version of the physics:
  \[ P E_{dr} = \frac{1}{2} \rho CDA V^3 + V F_n + \Delta PE/\Delta t + \Delta KE/\Delta t \]

  • \( P \) = power output of the cyclist
  • \( E_{dr} \) = drivetrain efficiency (0.97 from Martin et al., 2006)
  • \( \mu \) = coefficient of friction between the bicycle and the track surface.
  • \( F_n \) = Normal Force
  • \( \Delta PE/\Delta t \) = change in potential energy over change in time.
  • \( \Delta KE/\Delta t \) = change in kinetic energy over change in time.

Note - The rolling resistance of a new 250 with race tires can be as low as 0.0015

Note about DLV, corner radii actually varies between 25.2 – 25.4 m. The model includes those details.
The equation

\[ P E_{dr} = \frac{1}{2} \rho C_{DA} V^3 + \mu V F_n + \Delta PE/\Delta t + \Delta KE/\Delta t \]

- The geometry (corner radii, etc) of the velodrome will affect the equation here.

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Difference between velodromes
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- This graph shows the speed one would go at different power outputs if you were at DLV, DLV without a hill, DLV with a coefficient of friction of 0.004, T-Town, and a 250m wooden track.
- As you increase speed, the differences between tracks actually decreases but its not significant.
- From this you can see rolling resistance is a major difference between DLV and other velodromes. T-Town is about 6% faster and a wooden 250 is about 7.3% faster.
- Although the curves look “parallel” they are actually converging at higher speeds because rolling resistance plays less and less of a role. So the slower you go, the more a different track will affect you.

```

Difference between velodromes
```

<table>
<thead>
<tr>
<th></th>
<th>Pursuit time at DLV</th>
<th>Pursuit time at LA</th>
<th>Model Prediction</th>
<th>% diff</th>
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<tbody>
<tr>
<td>Dan H.</td>
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<td>05:11.8</td>
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<td>Valentin T.</td>
<td>05:38.5</td>
<td>05:22.7</td>
<td>05:21.3</td>
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<tr>
<td>Evelyn E.</td>
<td>04:37.5</td>
<td>04:29.6</td>
<td>04:23.7</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

- So with this can you predict performance at other velodromes?
- Here is data from three people from DLV that went to LA.
- When corrected for air density AND the track, the model can predict performance. The model does assume the rider provides the same power output between pursuits. A difference in power output may explain the difference in the last pursuiter.
**Difference between velodromes**

<table>
<thead>
<tr>
<th></th>
<th>DLV - T-Town</th>
<th>Pursuit time at DLV</th>
<th>T-Town Pursuit time</th>
<th>% diff</th>
<th>Model Prediction</th>
<th>Model Prediction with 8mph wind</th>
<th>% diff</th>
</tr>
</thead>
<tbody>
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<td>Matt L.</td>
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<td>03:42.8</td>
<td>03:37.8</td>
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<td>03:42.4</td>
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<td>Neal S.</td>
<td>03:52.4</td>
<td>03:46.8</td>
<td>03:39.3</td>
<td>-2.5</td>
<td>03:44.2</td>
<td>03:44.2</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

- The same was done with two juniors that went to T-Town.
- When corrected for air density AND the track, the model did NOT accurately predict performance.
- So what happened? Wind.
- The air was calm at DLV but windy at T-Town. The model was redone in an attempt to include wind. Wind during that time was variable from 6-10 mph. The event was remodeled with an 8 mph wind.
- Now the model accurately predicted performance.
- Note – I didn’t think it was going to work.

**Conclusion**

Dick Lane is slower because

- Rolling Resistance
- Tight Corners
- The Hill

**Questions?**

Thank You
- Tim Gallagher
- Pete Antonvich
- Lucuis Williams IV
- Brilliance Photography
- Everyone at the Dick Lane Velodrome

- Well that was a lot of information. Thanks for sticking through it all. Hope you learned something.
- Questions? Email me, Lee@gatech.edu
**Air Density**

- **Altitude/barometric**

  Bonus slides
  - Altitude increasing means air density decreasing and the cyclist’s ability to produce power decreases.
  - Graph showing “optimal” altitudes for the hour record.

  - Power = Torque times rpm
  - Torque is related to cadence, thus gear selection
  - Fatigue is related to torque so gear selection should matter.
  - This is the model’s version of “optimal” gear ratios.
  - BUT….
  - The model does not know the penalty associated with high cadence so it is only showing you half the answer. What is the penalty associated with high cadence specific to the pursuit? Well, I don’t know but that would make a great study….