Detecting Intensity: Automated Training Zone Calibration Module

* = Unique to Performance Lab

Background:

One of the most important aspects of training intelligently is understanding intensity. Two people, for example, can exercise at the same heart rate but experience widely varying levels of effort.

In Figure 1, a heart rate of 120 beats/min might be bordering on Anaerobic Threshold intensity (80-90% of max effort) for a 70 year old (A) but only at a weight management intensity (60-70% of max effort) for a 25 year old (B).

![Figure 1. Table Showing that Heart Rate Usually Declines with Age (1 beat per year).](image)

Depending on talent and training, some people will feel that running at 4:30min/km (7:14min/mi) pace is slow while others will perceive it to be near their maximal effort.

If a person is to exercise intelligently one of the major roadblocks to success is working out what ‘intense effort’ is. Fortunately, over the years and with the invention of the heart rate monitor in the early 1980’s, methods have evolved for establishing training intensity guidance often called Training Zones.
Physiological Benchmarks:
There are three primary benchmarks in human physiology to determine Training Zones,

- Maximal effort (VO2max, Critical Power),
- the Anaerobic Threshold
- and the Aerobic Threshold.

(See Figure 2).

Figure 2. Aerobic Threshold, Anaerobic Threshold and Maximal Effort as Determined in a Conconi Test.

Maximal Effort:
Maximal effort or Critical Power is as it states, the highest short term sustainable effort which usually relates to a VO2max effort in a sports science lab test. (near the maximum heart rate attainable.)

Anaerobic Threshold:
The Anaerobic Threshold is the zone where the body moves from predominantly aerobic to predominantly anaerobic effort. There is no actual threshold, it is more of a zone but the concept is useful in exercise.

The term Anaerobic Threshold can also be called the Functional Threshold, Lactate Threshold and a number of other less well known terms, which all basically describe the same concept in terms of its real world use by athletes and coaches.

Aerobic Threshold:
The Aerobic Threshold occurs when the athletes body begins to move away from a resting/low activity state to breathing more rapidly and where heart rate begins to rise steadily.

Both the maximum effort and Anaerobic Threshold are the most effective benchmarks to ascertain Training Zones.

Physiological Benchmark Testing:
Initially heart rate Training Zones were calculated by various calculations such as 220 minus the age of the athlete or the Karvonen formula. ([HRmax – HRrest] x Intensity) + HRrest
The first to achieve a relatively accurate assessment of intensity for an individual in an accessible way was Dr Francesco Conconi, a famous Italian physiologist who developed the Conconi Field test that helped cyclist Francesco Moser break cycling’s most arduous World One Hour Time Trial Record.

![Image of Francesco Moser during a One Hour Record Attempt.](image)

**Figure 3. Francesco Moser During a One Hour Record Attempt.**

What Conconi needed was a way of estimating the maximum sustainable intensity, for an elite cyclist riding for one hour, finding a heart rate that Moser could ride to.

Fortunately, there is arguably such a conceptual benchmark in human physiology that estimates this; the Anaerobic Threshold. The Anaerobic Threshold is usually defined as the maximum intensity that a human can exercise at for between 20mins and 1 hour. 20 mins if you are a beginner or less fit/trained and 1 hour if you are a highly trained elite athlete.

Conconi invented the test initially for runners and then converted the test to cycling. The rider gradually increases speed in stepped increments of short duration and continues to do this until they reach maximal effort.

Human physiology has a wonderful response where heart rate rises in a linear relationship to workload. (Figure 4A) That is, until it reaches a deflection point (B) where heart rate begins to plateau. The work requirement is still linear so the fact that the heart rate is plateauing means there is a shortfall to cover the physiological cost of the effort (C). This is covered by the Anaerobic system which means the deflection point is the Anaerobic Threshold. At least that is how the story went.

![Diagram showing the relationship between heart rate and speed with corresponding labels A, B, and C explaining the deflection point.](image)

**Figure 4. Conconi Field Test to Identify Anaerobic Threshold (FTP, LT) with corresponding Heart Rate and Speed Values.**
In actual fact, the body uses both aerobic and anaerobic energy throughout the full range of intensities. (Figure 5)

![Figure 5. Proportion of Anaerobic and Aerobic Energy for Popular Running Distances](image)

Still, the concept of a threshold has remained popular and is used preferentially to establish Training Zones. (e.g. Functional Threshold used by TrainingPeaks and Lactate Threshold used by Firstbeat.) See: Metric Reviews – Comparing ARDA to 1. TrainingPeaks, 2. Firstbeat.

Once the physiological benchmark is identified, the Anaerobic Threshold heart rate (Figure 6A) can be used to establish the corresponding power and speed Anaerobic Threshold values (6B).

From here all the other personalised Training Zones can be calculated. (Figure 6)

![Figure 6. Heart Rate and Speed Training Zones Established from a Conconi Field Test](image)

- Speed and Power Training Zones are a measure of the work output of the athlete, the action.
- Heart rate Training Zones are a measure of the athlete’s physiological intensity, the reaction.

Both are useful and ideally a measurement of the heart rate (the reaction – Figure 6A) and speed or power (the action - 6B) are both measured.

Over time other methods have been used to determine Anaerobic Threshold, the Lactate Threshold test being the most well known. (Figure 7)
Limitations in Using Anaerobic Threshold to Calculate Training Zones

Anaerobic Threshold tests are very effective but also have some big limitations;

- The tests are invasive in that the user has to remove a training day and substitute it with the Anaerobic Threshold test. (often with a few days of tapered training beforehand.)
- The test is quite taxing meaning other more race specific training is sacrificed at the same time.
- The tests require some level of experience in both execution (e.g. stepping the intensity correctly) and obtaining the data. (e.g. blood handling procedures in the case of a LT test.)
- The results need some expertise in analysis and in calculating the Training Zones.

For most people, obtaining Training Zones is hard to get organised and do.

The Ideal Training Zone Experience

Ideally, obtaining Training Zones should:

- occur as part of your exercise without having to stage any strenuous or invasive test,*
- the zones should calculate themselves for you,*
- and then automatically integrate into your exercise program for use when needed.

This is precisely what Performance Lab’s auto-calibration system does and it is the only system in the world that can accommodate the criteria above.

Calibration System Overview

Performance Lab’s calibration system automatically measures or infers the Anaerobic Threshold of an individual and then calculates their Training Zones.

Performance Lab can automatically calibrate:

- heart rate training zones,
- and speed/pace training zones,
- or power training zones. (Figure 8)
The Training Zones (Figure 9A) match specific benchmarks in human physiology. (9B)

There is also significant agreement in the demarcation of Training Zone boundaries (A) within the field. (9C)

Speed and power classifications have slightly more zones than heart rate classification systems. This is because when measuring speed and power, there are a number of Anaerobic zones used that cannot be differentiated by heart rate zones. Once heart rate zones reach intensities above Anaerobic Threshold, heart rate zones can only indicate that the effort is now Anaerobic. (9D)

Required Sensors

Required Sensors

Speed, Pace and Power Zones

Running/Walking - GPS or a footpod for speed and barometer or DEM to measure terrain (which is present in most smart phones).

Cycling – a purpose built cycling power meter is required.
Heart Rate Zones
Heart rate requires either a heart rate strap or optical heart rate measure only. Highest accuracy is achieved when speed, terrain and heart rate are all present.

Calculating the Anaerobic Threshold Heart Rate
Performance Lab’s calibration learns the user’s Training Zones as they exercise.

The calibration system monitors their heart’s reactions to activities looking for key physiological signatures in the data while the user goes about their normal exercise.

There is no test.

Once the system is able to identify the Anaerobic Threshold, it then takes a little more time to pass a confidence test before it allows the Training Zones to be calculated and provided to the user.

This process usually takes between 60 minutes and 2 hours depending on the experience of the athlete and the training data provided.

Calculating the Anaerobic Threshold Speed and Power
Speed and Power Training Zones can be calculated concurrently. The Anaerobic Threshold Power is used to calculate the power zones first and then speed zones (km/hr/mph) or pace zones (min/km, min/mi) are then translated from power.

Once again, no test is needed and a confidence test must be passed before the Training Zones are released to the user.

Types of Calibration: Quick and Full
Because some user’s may want their Training Zones predicted faster, Performance Lab has a

- Quick Calibration
- followed by a Full Calibration.

The Quick Calibration does not try to directly determine the user’s Anaerobic Threshold but instead predicts where it might be using other physical benchmarks which makes the calibration faster; 90 minutes. (2-3 workouts usually)*.

The Full Calibration focuses on directly identifying the Anaerobic Threshold and the time to calibration varies but usually takes about 2 hours*.

The Quick Calibration only uses power and Full Calibration uses both heart rate and power.

- If a user for example has a smart phone and heart rate or a purpose-built device, the Quick Calibration occurs first followed by the Full Calibration.
- If no heart rate is available (e.g. a smart phone), only the Quick Calibration is used*.

In Figure 10, you can see the initial predicted power Quick Calibration (P) before the Full Calibration (R) reaches a level of confidence to be used.
The Training Zone calibration never stops checking to see if the zones should be updated. This means that as the runner becomes fitter and faster or as they detrain, their training zones always match their current condition. (see Figure 10 where there is a calibration for each workout.)

There is no need to keep repeating invasive strenuous tests to keep the Training Zones up to date. (as is the case for TrainingPeaks to retain accurate analysis) See: Metric Review: TrainingPeaks

Also notice in Figure 10:

- Even with the predicted calibration, the system waits until workout 5 when it is relatively sure of an accurate calibration. (the score out of 10 is the level of confidence),
- In workout 7, the Full Calibration (R) is used, the system then changes its mind and goes back to the Quick Calibration (P) in workouts 8 and 9, before finally settling on a Full Calibration (R) in workout 10,
- The Quick and Full Calibration values are very similar.

Finally, in Figure 10 in terms of Anaerobic Threshold calibration,

- a predicted power for Quick Calibration occurred within 5 workouts (101 mins),
- a Full Calibration of power occurred within 10 workouts (242mins),
- and a heart rate calibration also occurred within 7 workouts (157 mins).

10 workouts may seem like a long time to calibrate but once this is achieved it never has to be done again.

This can be compared to Firstbeats Lactate Threshold calculation which can be prone to error calculating Lactate Threshold pace values. This is probably because Firstbeat’s algorithms do not include terrain in their calculations. See: Metric Review: Firstbeat

See Figure 11 from the Garmin Connect website (using Firstbeat), that the Lactate Threshold pace values for a 50 year old recreational runner are 1:31min/km (2:26min/mi) and 1:27min/km (2:20min/mi).

This is faster than world record pace.

A similar comparison to Anaerobic Threshold effort (being the highest sustainable pace for an hour) is the Half Marathon World Record of 58mins 23 seconds. This average pace was 2:46min/km (4:27min/mi) which is over a minute slower than the pace predicted for the recreational runner.
Manual Calibration

If an athlete has already had their Anaerobic (Functional, Lactate) Threshold assessed (e.g. sports science lab), or is particularly attached to their known Training Zones, Performance Lab offers the opportunity to override auto calibration and use a manual Anaerobic Threshold setting.

This involves entering in their Anaerobic Threshold Heart Rate or Anaerobic Threshold Pace into the app (figure 12A). This provides the lower boundary of the Anaerobic Threshold and all further Training Zones are then calculated. (12B)
Stability of Training Zones

In figure 13, we can see the Performance Lab calibration system is very stable in its detection of Anaerobic Threshold and therefore the runner’s Training Zones.

Note that:

- Anaerobic Threshold power increases (250-266 watts) with fitness improvement.
- Anaerobic Threshold heart rate remains almost 100% consistent at 182bpm indicating increased fitness (182bpm = 250 watts and then 182bpm = 266 watts)
- The confidence scores move from a less confident 5 to finally settling on a very confident 9 out of 10.

Data Filters

The calibration systems superior ability has a lot to do with Performance Lab’s data filtering which means only genuine accurate data is accepted for calibration. In Figure 14, using power-heart rate relationships, the green shaded areas are data that is accepted for calibration and the clear areas are data values that are believed to be erroneous which are discarded.

Figure 14A shows a situation where the speed sensor dropped out for a period of time.

14B shows erroneous data which is harder to detect where there are only subtle changes in the data.
Potential Error Issues that the Calibration System Manages

Quick Calibration Error Management

Poor Terrain Measures (e.g. Faulty Barometer, GPS Altitude or Bad DEM)

Poor terrain measures (i.e. inaccurate gradient) effect the power values. Bad Terrain can be resolved in most areas of the world by applying a Digital Elevation Model with a resolution of 8 meters or less. Heart rate is used to filter bad data.

Poor Speed Measures (e.g. GPS in Urban Canyons or Under Dense Foliage.)

Bad GPS speed can also be filtered out using heart rate and other physical benchmarks to ensure clean speed data for calibration.

Full Calibration Error Management

Erroneous data: Dry Heart Rate Straps

One of the biggest issues with calibration data is dry heart rate straps. This usually occurs at the start of a workout (first 15mins) when the chest strap is not made wet beforehand, particularly in colder drier conditions.

It also happens in both cycling and running when exercising for a prolonged time into a head wind. In each case, the strap dries out causing conductivity issues that lead to usually overestimated heart rate values. This happens in most outdoor heart rate monitored workouts but the users don’t notice.

In Figure 15, the gray vertical line marks a point where the heart rate (in red) is very high. In the right-hand box labelled Raw Data in the graphic we can see that the heart rate at this point is 209 beats per minute! As soon as the person is sweating enough, the conductivity improves and the heat rate drops to the accurate 120-130 beats per minute. The calibration system filters the bad heart rate data out.
Erroneous data: Loose or Improperly Fitted Optical Heart Rate Devices

Optical heart rate has a slightly different issue where the watch is not firmly on the wrist which effects the optical detection causing heart rate measurement error.

Once again, the Performance Lab filter system can detect that the heart rate to power relationship is not accurate which means it’s stops the data from being used by the calibration system.

Calculation of Training Zones

Training Zones are calculated once the Anaerobic Threshold has been ascertained.26

Figure 16 below indicates how both power and heart rate zones are calculated based on the Anaerobic Threshold. Speed zones are translated from power zones.

Figure 15. Example of a Dry Heart Rate Strap at the Start of a Workout Seen in the Workout Viewer.

Figure 16. How Training Zones are Calculated for Both Heart Rate and Power. (Speed/Pace is Translated from Power.)
Use of Training Zones

In the Plan

Once the runner is calibrated, this information is passed on automatically to their exercise plan (if they have one). This means that the training plan now knows what the effort level should be for every workout that the user will engage in. Figure 17 shows the Performance Lab exercise auto plan builder which contains each scheduled workout and the corresponding training intensities. See: A Machine That Can Write a Custom Training Program: Exercise Plan Builder Module

Every time the runner chooses to do a workout, the system knows what the plan is and exactly what personalised intensity the runner should do the workout at.

In the workout

Start of workout

When the runner or cyclist starts their workout in the app, the system knows the training intensities for each aspect of the workout. (Figure 18 Running and Cycling Zones for a user.)
The system tells the user what the workout is and provides the details on precisely what intensities to train at during the workout. (Figure 19)

![Image](image1.png)

**Figure 19.** A Workout Introduction for a Cyclist providing a. the Total Distance of the Workout, b. the Types of Training Scheduled and the Power Training Intensities Associated with each Training Type in the Workout Viewer.

**During the Workout**

If the runner or cyclist is doing speedwork in the session, once they are exercising, the system detects when they engage in the scheduled types of training and provides guidance around the correct intensity.

For example, let’s say that the user is scheduled to do Up Tempo training that includes 2 reps of 4mins. (Figure 20)

![Image](image2.png)

**Figure 20.** A Speed Training Session in the Workout Viewer Determined by Speed Training Zones.
As the user begins to increase speed to do an Up Tempo rep, the system detects this and says ‘approaching up tempo’. This is important because most people do their speed training too hard so the ‘approaching up tempo’ comment is to let the user know that they are nearing the zone and should begin to accelerate more gently to move into the zone. This prevents overshooting.

Once they enter the correct Training Type, the system confirms this by saying “Up Tempo.”

The system now provides pace values audibly to assist the user in staying in-zone. Let’s say the Training Zone is 4:55 to 4:23 min/km. (7:54 min/mi to 7:03 min/mi)


The runner can hear that they are in the zone and whether they are in the top or bottom of the zone which helps them control their effort.

Every 15 secs the runner gets a duration update (e.g. 15s, 30s, 45s, 1min, 1min 15s etc) so if they have a 4min rep to do, they know both the correct intensity and duration.

If the pace moves slightly out of zone, the system will provide an out of zone warning to allow the user to choose to re-enter the zone.

This provides very easy efficient training with precise durations and intensities being monitored by the system because it can detect what is happening. See: Interpreting Exercise Data: Guidance and Coaching Module

Validation

The goal is always to have the most accurate calibration. In situations where the user has both speed, terrain (barometer) and heart rate sensors, they will receive a Quick Calibration followed by a Full Calibration.
If the user has speed and terrain only (e.g. smartphone), the Quick Calibration is provided solely.

Manual Calibration is always available.

**Running Calibration**

**Quick Calibration Predictive Model: (Power only)**

The tight calibration for the predictive model was 73.3% within 5% of the known Anaerobic Threshold and 95.9% for the loose calibration within 10% of Anaerobic Threshold.

This is based on a minimum 20 minutes of running using 4087 verification data sets.

**Full Calibration Model: (Power and Heart Rate)**

For each calibration experiment, three values were recorded;

- the percentage of calibrations within a tight acceptance band,
- the percentage of calibrations within a wide acceptance band,
- and the average time to calibrate.

The loose Calibration Format (12 bpm maximum RMS error):

- 88% within the tight band
- and 98% within the wide band
- average time to calibrate: 2 hours 31 minutes (3650 verification data sets)

The tight Calibration Format (6 bpm maximum RMS error),

- 97% within the tight band
- and 99% within the wide band
- average time to calibrate of 3 hours 14 minutes (2336 verification data sets)

**Heart Rate Model: (Heart Rate Only)**

The tight calibration format (within 2bpm) was 89.7% within the known Anaerobic Threshold and loose calibration format resulted in 95.2% within 4bpm for 4952 verification sets.

Average time to calibration was 3hrs 26min and 3hrs 25min respectively.
Cycling Calibration:

Predictive Model: (Quick Calibration or Power only)

The tight calibration (within 10 watts of the known Anaerobic Threshold) was 92% and the loose calibration within 20 watts was 99%.

Full Calibration Model: (Power only)

The full cycling calibration showed 91% within 10 watts and 99% within 20 watts of the known Anaerobic Threshold.

Although there appears to be no value here having the Full Calibration model for cycling, we still use it because it is a direct measure of the Anaerobic Threshold.

Calibrating Other Activities:

The calibration systems used can be converted to many other activities including gym training, exercises that use body weight like Crossfit, monitoring soldiers effort levels in the field and weight loss type exercises like walking.

Summary:

Performance Lab has highly accurate and diverse methods to provide users with heart rate, speed or pace and power training zones.

See:

- Technology and IP Overview (Performance Lab)
- New Exercise Paradigm ‘Closing the Loop’: Consumer Experience
- Detecting Activity: Contextual Classification Module
- Exercise Plan Builder Background/Validation
- Measuring Performance: Fitness and Fatigue Measures (Cardio Performance Module)

References:

8. Janssen P. 2001. Lactate Threshold Training. Champaign (IL) U.S.A. Human Kinetics. p. 16 Figure 1.1
12. Polar Heart Rate Monitor Support page: https://support.polar.com/en/support/Heart_Rate_Reserved_HRR
19 Janssen P. 2001. Lactate Threshold Training. Champaign (IL) U.S.A. Human Kinetics. p. 70. Figure 3.2
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25 Performance Lab Whitepaper: Metric Review: Firstbeat VO2max and VO2max Dependent Metrics
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