# DESIGN AND CONSTRUCTION
# OF AN
# ULTRALIGHT TRACK BICYCLE

by

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Thesis Supervisor

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Chairman, Departmental Committee on Theses

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# THE DESIGN AND CONSTRUCTION OF AN ULTRALIGHT TRACK BICYCLE

## ABSTRACT

A track bicycle has one fixed gear, no brakes, and is raced around a banked, oval track. Since rapid acceleration is of primary tactical significance, a lighter bicycle is desirable. This thesis was an attempt to reduce the weight of a track bicycle from the usual 18 or 19 pounds while retaining the necessary strength and rigidity. This was accomplished by several design changes employed in conjunction with the extensive usage of both aluminum and titanium alloys. The bike constructed weighs 12.5 pounds and is strong enough to be ridden successfully on the road.

# ACKNOWLEDGEMENTS

This project was jointly funded by the Mechanical Engineering Department and a Clapp and Poliak Engineering Design Award through the M.I.T. Undergraduate Research Opportunities Program, for which the author is very grateful. Constant assistance was provided by Mr. Ralph Whittemore, Mr. Ralph Bowley, and Mr. Fred Anderson; without them nothing gets done in Building 35. Interest and advice was enthusiastically supplied by Professors Steve Loutrel, Shawn Buckley, and Woodie Flowers. Mr. Edward Harrow of Raleigh Industries was helpful in providing information and in equipping the bike.

Photographs were taken by Margo Foote, and typing by Anna Piccolo.

Many thanks to all these kind people.

# INTRODUCTION

A bicycle with less mass will accelerate faster than one with more mass for a given force input. Track racing consists of a pack of riders slowly circling the track until one (or more) rider "breaks" from the pack. The rest of the pack will try to stay with him and "draft" him, using him to break the wind and consequently reducing their own power output. A light bike would therefore be tactically useful in enabling a rider to break more easily by having an acceleration advantage. However, weight cannot be pared off at the sacrifice of strength and "stiffness". Stiffness is a term which a racer uses to describe the resistance to bending his bicycle exhibits (its rigidity). It is probably the most important criterion by which a racing frame is judged, as frames never break in normal racing conditions, which indicates that strength is not a problem.

The normal track bike weighs 18 or 19 pounds. It has a sophisticated steel frame which is made of butted tubing. This tubing is thicker at the ends where the tubes are joined because stresses are higher there. Its other parts are either steel or aluminum alloy.

The author has knowledge of two attempts at constructing an ultralight track bicycle. The first was a bike built for World Champion Eddy Merckx for use in an attempt to set a new one-hour record. (He was successful, riding over 31 miles in an hour on a track). The bike used a very lightweight steel frame, which was much less rigid than a normal track bike. However, since Merckx was to pedal at a constant speed with no accelerations this was considered acceptable. The components on the bike including custom built titanium handlebars, stem, and seatpost. His pedals were partly plastic and he didn't use a lockring for the track sprocket. He used 24 spoke wheels of extreme lightness. The tires were expected to last a maximum of 4 hours on a smooth board track. Finally, the components were extensively drilled out for lightness, at an obvious cost in both rigidity and strength. The bike weighed 13 1/4 pounds, and was obviously quite restricted in usage.

The second attempt was a bicycle built by Raleigh Bicycles. It used a frame constructed of tubes made of carbon-boron fibers. Once again, frame rigidity was less than on a normal track bike. Other components such as wheels were similar to those on Merckx's bike, and the bike was similarly restricted in its ridability. It was also extremely expensive, due to the cost of the fibers in the frame ( 60 dollars/pound). However, due to the weight saved in the frame it was about one pound lighter than Merckx's bicycle.

Both these attempts had sacrificed strength and rigidity to light weight. It appeared that in both cases the approach was wrong. Although both bikes represented large investments and a lot of time, it appeared that these resources were misapplied, and the results were generally unsatisfactory. The problem remained to significantly lighten the bike while retaining strength and rigidity.

## DESIGN GUIDELINES

In approaching the problem, several design guidelines were formulated.

(1) Use of larger diameter tubular components in tubular applications. The standard track bicycle consists of many tube type parts: the frame, the seatpost, the seat undercarriage, the hub axles, the handlebars, the pedal axles, and the crank axle. In a tube in either bending and torsion, the strength and rigidity go up as the cube of diameter. Therefore, it was decided that unless geometrically or otherwise constrained, larger diameter components would be used to lighten the structure while keeping the same rigidity and strength.

(2) Use of sealed, precision bearings. The bearings in regular bikes are adjustable angular contact bearings. They are not sealed and are therefore vulnerable to contamination. They are of poor quality, especially when one considers that they are adjustable. This means that the running clearances are set by screwing a bearing core on a threaded surface relative to a fixed bearing race. Since this is done by hand it is obviously subject to error. On the other hand, sealed precision ball bearings are one piece cartridges which are constructed with the proper clearances. They are not subject to contamination and they are of higher quality than the bearings in the finest track bicycle components. Also, they are lighter and easier

to incorporate in component design.

(3) Adjustability. Many track racers ride custom built bicycles that incorporate unneeded adjustment features for the seat and handlebar positions. These are unneeded because a racer who orders a custom bike knows his relative seat- pedal- handlebar-dimensions and should have them built into the bike. The micro-adjusting seatpost used on almost all racing bikes weighs 12 ounces and once set is of no more use than a 6 ounce nonadjustable one. Racers ride for years without varying saddle height, handlebar position, etc. Therefore, the design would incorporate the known dimensions of the author and sacrifice adjustability to weight savings.

(4) Use of alloys. The standard track bike uses a lot of steel where aluminum and titanium could be substituted. Since a top track bike costs about $500 it doesn't seem unreasonable to use these more costly materials, which can save weight when properly used. 6061-T6 aluminum was used where welding was done because of its superior weldability. It has a yield strength of 40,000 psi. 2024-T4 aluminum was used wherever else aluminum was employed. Its yield strength is 47,000 psi. The titanium alloy used is Ti 6Al 4V, with a yield strength of 150,000 psi.

# DESIGN

## Frame

As stated before, the major criterion by which a frame is judged is its rigidity. The diameters and thicknesses of the tubing used in normal track bikes were known, and therefore their stiffness could be computed and matched by the chosen tubes in the new frame.

The frame is one area where some of the tube diameters can be increased. However, the thickness of existing tubes is already down to .020 - .025". Increasing the diameter is done in conjunction with decreasing the thickness, and the steel tubes would get prohibitively thin-walled and prone to buckling. Therefore another material was needed.

When they do fail, frames fail in compressive buckling (see Table I). A look at common engineering materials (steel, titanium, aluminum, and magnesium) shows magnesium to be the best material per unit weight in compressive buckling. However, it corrodes, is brittle, and is difficult to extrude. The next best choice is aluminum. Unlike titanium, it is easy to weld and fabricate. And in compressive buckling it is more than twice as efficient as steel. Due to its light weight and smaller modulus of elasticity aluminum must be used in larger diameter tubes to be really efficient in rigidity. The stiffness of the frame is a function of the stiffness of the tubes in bending and torsion. In order to determine what the main frame tubes should be a constraint was put on the diameter/thickness ratio limiting it to a maximum of 50:1. It was felt that if this was exceeded the frame would be overly prone to impact buckling. This D/t ratio can be plugged into a formula which translates a tube of one material, diameter, and thickness into another material.

$$E_1 D_1^3 t_1 = E_2 D_2^3 t_2$$

If one assumes that D/t = 50 then t can be replaced in the formula by D/50. This reduces the problem to one unknown, $D_2$. It was decided to turn the tube thickness down in the middle length of the main tubes to approximate the butting of the conventional steel tubes. Therefore, a typical tube calculation would be as follows.

Down tube - middle part of tube

$$E_S D_S^3 t_S = E_A D_A^3 t_A$$

$$(30 \times 10^6 \text{ psi}) (1.125 \text{ in})^3 (.024 \text{ in}) = (10 \times 10^6 \text{ psi}) (D_A)^3 (D/50)$$

$$D = 1.5 \text{ inches}, t = .030 \text{ inch}$$

Therefore the decision was made to use 1.5 inch diameter aluminum tubing. The wall thicknesses were calculated and increased somewhat to provide an extra margin of stiffness and strength. All the main tubes began as 1.5 inch diameter, .049 inch wall thickness 6061-T6 aluminum tubing (6061 was chosen because of its weldability). Similar calculations were made for the tubes in the rear triangles, which were tapered and sized accordingly. The chainstays are constrained due to wheel and chainring clearance, and are therefore .750 inch O.D. with a wall thickness of .083 inches at the bottom bracket and tapering to .045 inches at the dropouts. Seatstays are .625 inch O.D. with a wall thickness of .065 inch tapering to .045 inch. The dropouts are .250 inch thick 6061-T6 plate. The bottom bracket has a 1.75 inch O.D. and was bored to fit sealed bearings with an O.D. of 1.375 inches.

A conventional track geometry was used in the frame design. With a 1.5 inch fork rake the wheelbase is thirty-eight and one half inches. Head angle/seat angle is 74°/74°. The bottom bracket clearance is eleven inches.

Keeping in mind the criterion of eliminating unneeded adjustability the author determined his seat to pedal distance on another bike and decided on an integral seatpost/seat for the bike. The seat tube continues up past the top tube and is welded directly to a partially cutaway tube which is the undercarriage for the seat material, which is a nylon Unicanitor saddle top separated from its conventional steel undercarriage. The result is a savings in weight of nearly a pound, which no sacrifice of anything except adjustability.

The frame was put into a jig to hold it in alignment and was joined by tungsten-inert-gas welding. After welding it was heat

## The Rear Hub

The almost unanimously used track hub weighs 11.5 ounces. It has conventional bearings with adjustable cones located on a threaded, solid steel axle. The axle is heavy and is stronger than it need be for smooth tracks that have no bumps. Once again precision sealed bearings were used, and a larger than usual diameter hollow titanium axle. The inside of the axle ends were threaded to accept bolts to attach the wheel in the bike frame. Having a bolt inside the axle ends increases the strength and rigidity there, where most of the stress is. This system is more efficient than the conventional axle nut method of attachment because it reinforces the axle at the end where it needs it, while not being any heavier. The axle itself is much lighter than the normal axle with equivalent strength, as are the sealed bearings. The hub body is bored like the bottom bracket to accept the bearings. It is made of 2024-T4 aluminum and is similar to standard track hubs, except that the section between the flanges is twice the normal diameter and is therefore lighter for the same strength. It was drilled for 32 spokes, and the whole hub weighs only five ounces.

## The Front Hub

The front hub is similar in design to the rear. It also has sealed bearings and a larger diameter, hollow titanium axle. Since there is no torque transmitted through the 2024-T4 hub body it has a wall thickness of only .020 inch between the flanges, which are drilled for 28 spokes. It is held in the front fork by a skewer that is threaded at one end with a one-winged wingnut that screws onto it. It works as a nut and bolt arrangement going through the axle. The finished hub and skewer weigh about three ounces versus the nine ounces of the conventionally used front track hub, which is considerably overdesigned for its loading.

## The Pedals

The pedals were designed to be comfortable, easy to get into (with toeclips), and good for increased cornering ability. Standard pedals make the rider's foot bear on two parallel ridges about 2 1/4 inches apart, perpendicular to the foot. This leads to bowing of the foot inward, which causes discomfort and inefficiency. Therefore the pedals built have platforms on which the whole ball of the rider's foot can rest. The platforms are rigid, strong, and quite comfortable. On the back they have a small piece that is bent down. When the rider steps on it the pedal swings up and it is easy to insert the foot into the toeclip. The toeclips bolt on the front of the platform as they do on conventional pedals.

Another change entailed locating the two bearings close together in the center of the pedal as opposed to at the ends. This does two things; it enables the axle to be shorter, and it increases cornering clearance. The shortened axle is made of titanium and is threaded to fit a standard crank arm. It weighs only 1.25 ounces compared with the conventional 4 ounces steel axle which isn't any stronger. The platform and the body of the pedal are 2024-T4 aluminum, and they attached to each other with epoxy and two countersunk screws. The method eliminates any need for welding and has proved to be strong enough. The epoxy used is rated at 3,000 psi in shear and there is one square inch of area which is used. The screws help in tension loadings and will also prevent any sudden failure of the epoxy from having catastrophic effects.

The bearings are pressed into the pedal body and onto the axle. The pair of pedals weigh 7.5 ounces, which cuts off 5 ounces of rotating weight from the lightest track pedals and increases the tactically important cornering clearance.

## The Handlebars and Stem

Track bikes have the bars down low to put the rider into an efficient sprint position. The way this is done is by using stems that angle downward and bars with a deep drop. The end result is a handlebar position on the level of the fork crown which is accomplished by the heavy, nonrigid and complex method of conventional bars and stem. Drop handlebars were developed to give the rider a variety of hand positions. However, a track rider and many road racers use only one position. Therefore, it seems to make sense to have the handlebars attached to the fork crown as directly as possible. This cuts out weight and adds important rigidity to the handlebars. The handlebar mounting end of a steel stem was silver soldered to a steel strip which was silver soldered to the top of the fork crown. A simple, wide shallow U shaped set of handlebars was used. This setup cuts almost a pound off the bike and is quite rigid.

## Additional Components

The wheels were built up using Hi-E Engineering tubular rims. These have a larger than normal cross-section and are made of 2024-T4 sheet riveted together. They weigh about 8 ounces and are very stiff for their weight. Torrington 14/16 gauge double butted stainless steel spokes were used. Pirelli Specialissimo Corsa leggero tires, medium weight (9 ounces) road racing tires were mounted with Tubasti rim cement. A standard track sprocket and chain were used. The crankset chosen was a T.A. cotterless crankset with a 48 tooth chainring. The bike was initially equipped with an 18 tooth rear sprocket to give a gear of 72 inches. A Stronglight competition headset was used. Attempts were made to obtain a conventional Reynolds 531 track fork but it proved impossible and a Raleigh roadracing fork was substituted. It was modified to give the required wheel clearance and the design fork rake of 1.5 inches.

# CONCLUSIONS

The finished bicycle is as rigid as a normal sprint track bike. Its final weight, with the wheels built up for road riding, is 12 pounds, 5 ounces. Equipped like Merckx's bike for all-out track racing it could be reduced to about eleven pounds. With increased time a front fork could be designed and built, and the crankset could be redesigned. It is felt that with an aluminum fork, titanium crankset, titanium spokes, and a titanium chain and rear sprocket that an ultimate weight of ten pounds or less could be realized. However, the existing bicycle is quite strong and rigid and appears to be the lightest sprint bike yet. Also, it would not be prohibitively expensive to build on a production basis if the demand was thought to exist.

## TABLE I FRAME MATERIAL COMPARISONS

| Material | F x $10^3$ | $\frac{lbs}{ins^3}$ | E x $10^6$ | Tension | Bending | Compressive Buckling |
|---|---|---|---|---|---|---|
| Steel | 185 | .29 | 30 | .70 | 1.44 | 2.12 |
| Titanium | 150 | .16 | 16 | .48 | .88 | 1.30 |
| 6061-T6 Al | 45 | .10 | 10 | 1.00 | 1.00 | 1.00 |
| Magnesium | 40 | .07 | 7 | .79 | .74 | .80 |

## TABLE II FRAME TUBE SPECIFICATIONS

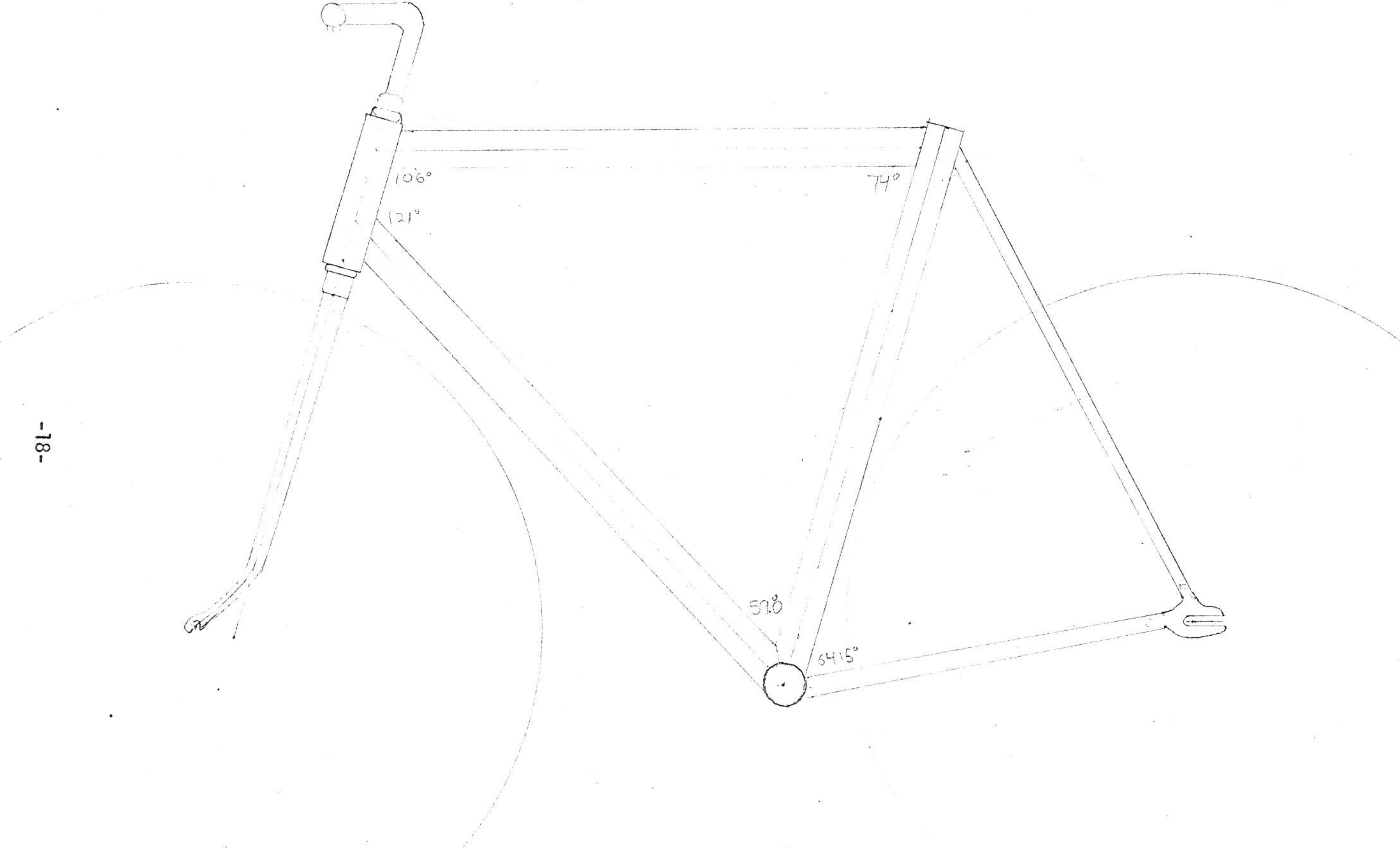
| Tube | Outside Diameter (in) | Thickness (in) |
|---|---|---|
| Top tube | 1.5 | .049/.032 |
| Head tube | 1.5 | .049 |
| Down tube | 1.5 | .049/.036 |
| Seat Tube | 1.5 | .049/.036 |
| Bottom bracket | 1.75 | .187 |
| Seat stays | .625 | .065 taper to .045 |
| Chain stays | .750 | .083 taper to .045 |

## TABLE III FRAME GEOMETRY SPECIFICATIONS

| | |
|---|---|
| Head angle | 74° |
| Seat angle | 74° |
| Size | 22.5 in |
| Top tube length | 21.75 in |
| Fork rake | 1.5 in |
| Drop | 2.36 in |
| Chainstay length | 16.0 in |
| Wheelbase | 38.5 in |

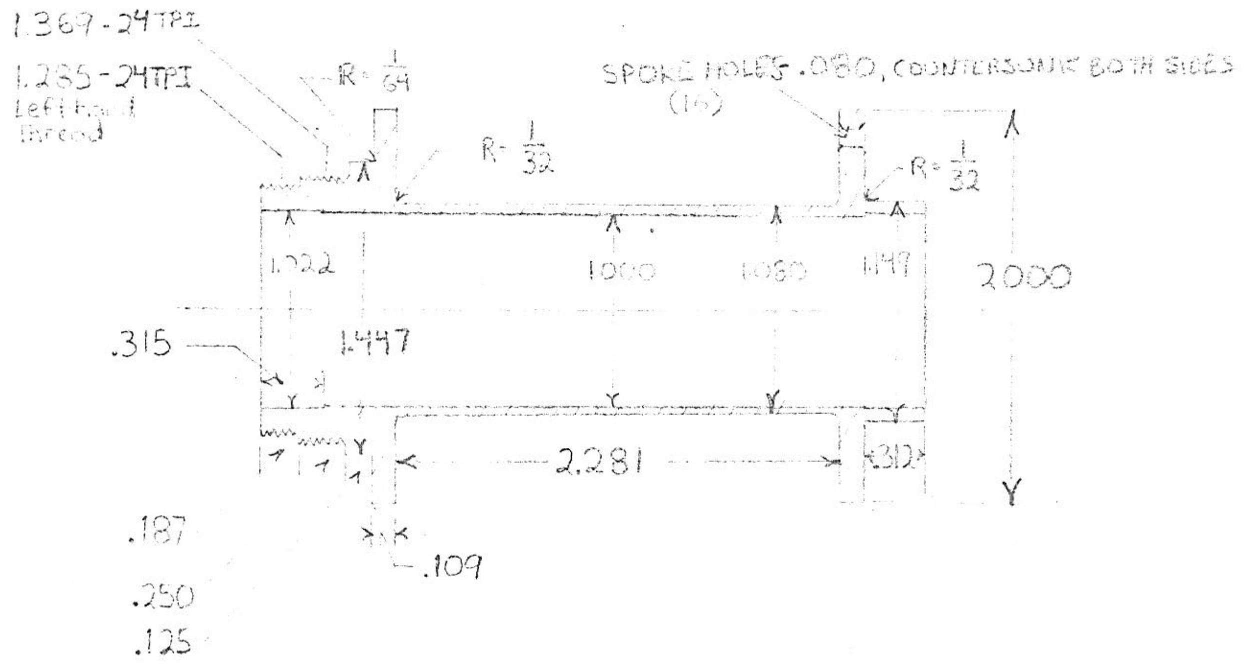
## TABLE IV BEARING SPECIFICATIONS

| Bearing | No.(New Departure) | O.D. | I.D. | Radial Load Rating at 1000 RPM Based on 3800 hrs. average life |
|---|---|---|---|---|
| Bottom bracket | Z99R10 | 1.3750 | .6250 | 245 lbs. |
| Rear hub | Z99-3L00 | 1.0236 | .3937 | 195 lbs. |
| Front hub | Z99R6 | .8750 | .3750 | 112 lbs. |
| Pedal | Z99R6 | .8750 | .3750 | 112 lbs. |



Frame Geometry

1cm. = 2 inches



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|---|---|---|---|
| **TOLERANCES**<br>(EXCEPT AS NOTED) | Rear Hub Shell 32 SPOKES | | |
| DECIMAL<br>± .[illegible] | 2024-T4 | SCALE<br>FULL | DRAWN BY<br>M. Rosenbaum<br>APPROVED BY |
| FRACTIONAL<br>± | TITLE | | |
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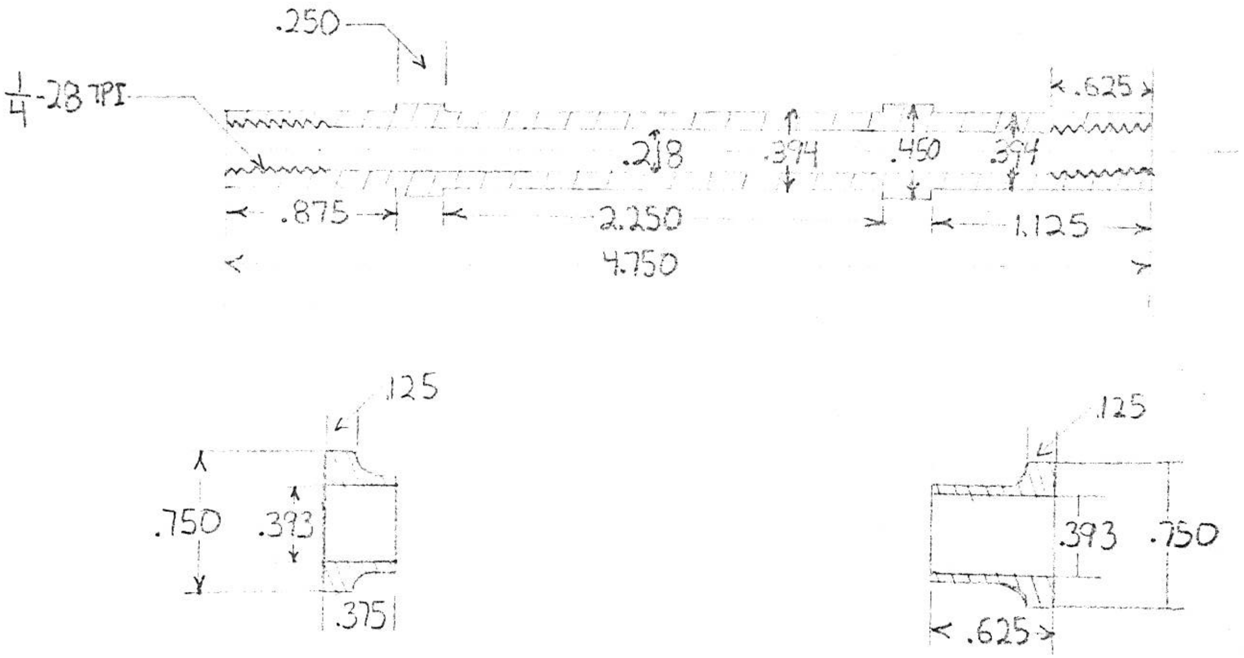

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|---|---|---|---|
| **TOLERANCES** (EXCEPT AS NOTED) | REAR HUB AXLE + SPACERS | | |
| DECIMAL<br>± .0005 | AXLE - Ti 6Al-4V<br>SPACERS - 2024-T4 | SCALE<br>FULL | DRAWN BY M ROSENBAUM<br>APPROVED BY |
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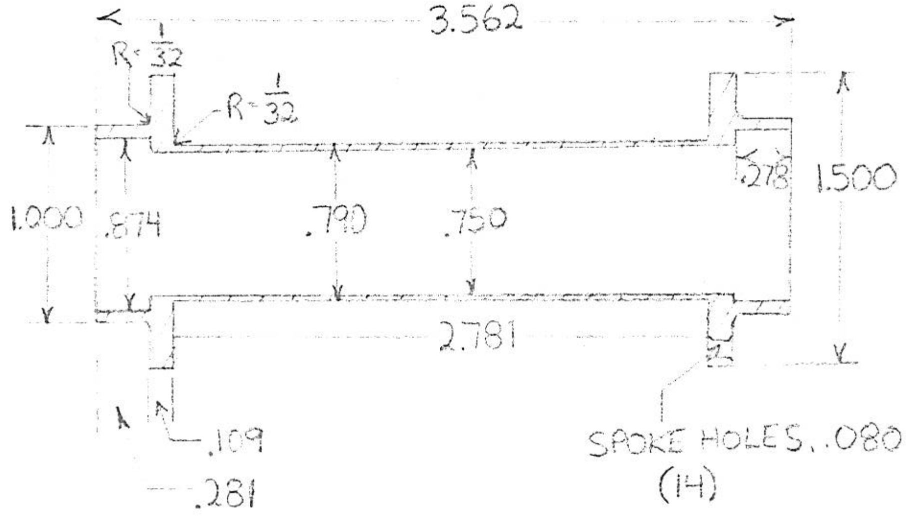

SPOKE HOLES, .080 - COUNTERSUNK BOTH SIDES
(14)

| | | | |
|---|---|---|---|
| **TOLERANCES**<br>(EXCEPT AS NOTED) | FRONT HUB SHELL 28 SPOKES | | |
| DECIMAL<br>± .0005 | 2024-T4 | SCALE<br>FULL | DRAWN BY<br>M [illegible]<br>APPROVED BY |
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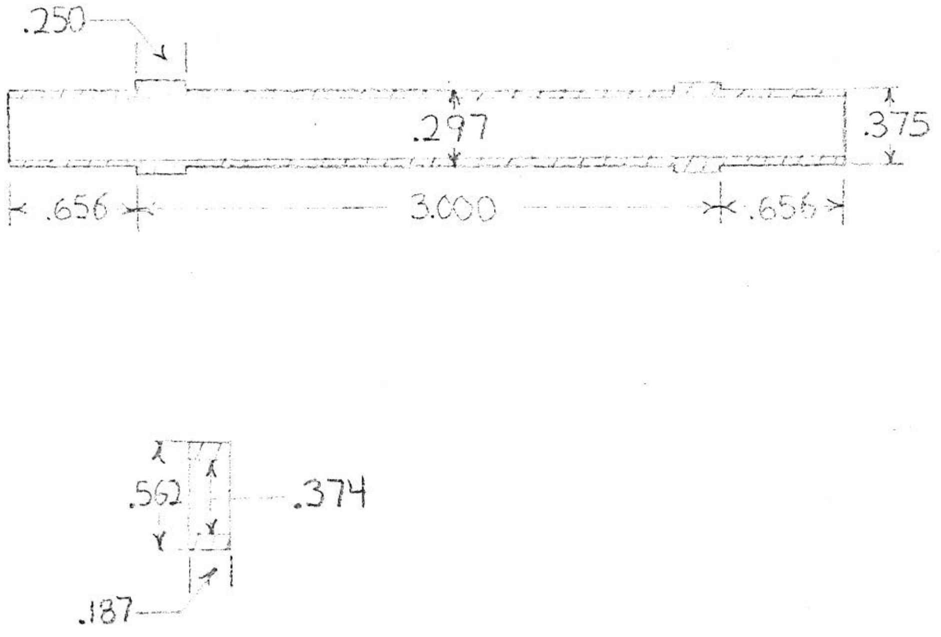

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|---|---|---|---|
| TOLERANCES<br>(EXCEPT AS NOTED) | FRONT HUB AXLE + SPACERS (2) | | |
| DECIMAL<br>± .0005 | AXLE - Ti 6Al 4V<br>SPACERS - 2024-T4 | SCALE<br>FULL | DRAWN BY<br>M. ROSENBAUM<br>APPROVED BY |
| FRACTIONAL<br>± | TITLE | | |
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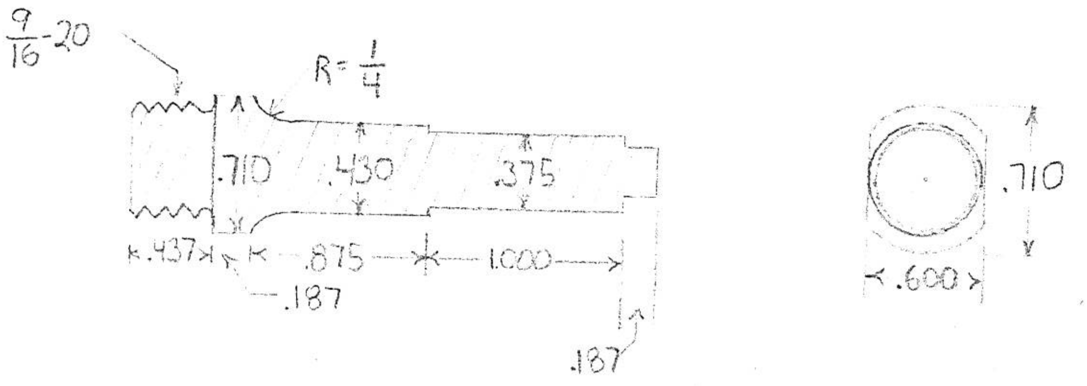

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|---|---|---|---|
| TOLERANCES<br>(EXCEPT AS NOTED) | PEDAL AXLE | | |
| DECIMAL<br>± .005 | TI 6AI 4V | SCALE<br>FULL | DRAWN BY<br>M ROSENBAUM<br>APPROVED BY |
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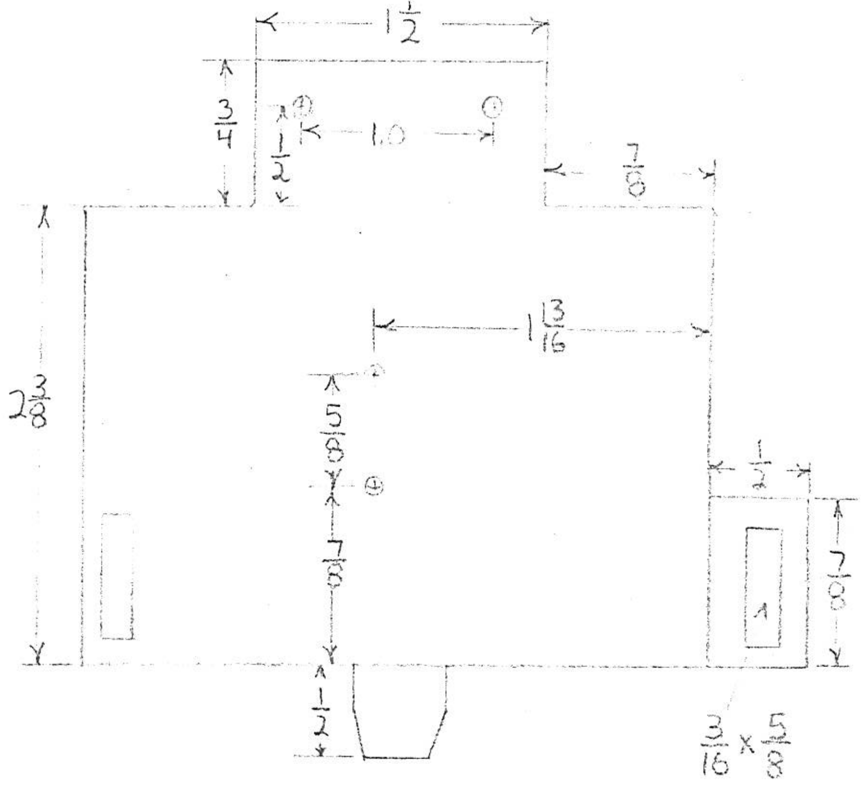

THICKNESS .094

| | | | |
|---|---|---|---|
| TOLERANCES (EXCEPT AS NOTED) | PEDAL PLATFORM (PRE-BENT) | | |
| DECIMAL<br>± | 2024-T4 | SCALE<br>FULL | DRAWN BY [illegible]<br>APPROVED BY |
| FRACTIONAL<br>± 1/3 | TITLE | | |
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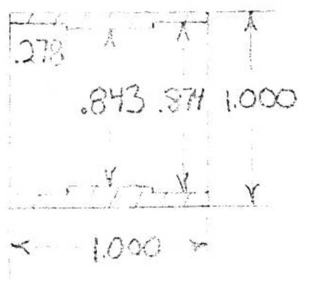

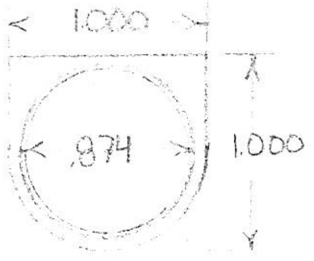

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|---|---|---|---|
| **TOLERANCES**<br>(EXCEPT AS NOTED) | PEDAL BODY | | |
| DECIMAL<br>± .0005 | 2024-T4 | SCALE<br>FULL | DRAWN BY<br>A. [illegible]<br>APPROVED BY |
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