



# Design of Urban Transit Rowing Bike (UTRB)

A Major Qualifying Project Report

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In Mechanical Engineering

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## **Abstract**

The objective of this project was to create a human-powered vehicle as a mode of urban transport that doubles as a complete exercise system. The project was constrained in scope by the requirement of affordability, under \$1,000. This was accomplished through reducing complexity by utilizing a cable and pulley drive train, simplified tilting linkage and electric power assist in place of variable gears. This project successfully demonstrates that rowing can be the basis for effective human powered urban transport.

## **Acknowledgments**

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Thanks to Derk F. Thys creator of the Thys Rowing Bike for his correspondence and for his foundational work on rowing geometry for biking.

Thanks to Bram Smit for his correspondence regarding the Munzo TT linkage and his experience building a variety of innovative recumbents.

Thanks to Bob Stuart, creator of the Car Cycle for his correspondence regarding his groundbreaking work and engineering insights. His experience was important to finding an appropriate project scope.

As a general rule, the human-powered vehicle community is very welcoming and open to innovative new ideas. It has been a great experience for the UTRB team to contribute to such a good-natured community.

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# 1 Introduction

Most people today use bicycles for a combination of exercise, recreation and utilitarian transport. Bicycles provide mostly a lower-body workout which is insufficient alone as a total-body workout. On the other hand, stationary rowing is a common form of exercise that provides a more complete full-body workout with an emphasis on the upper body.

If exercise is as important a focus as locomotion of the bike design, then the ideal bike is one that utilizes rowing instead of peddling as the mode of power delivery. This combination preserves the utility and recreational value of a bike while improving its exercise component by incorporating more core and arm strength in every stroke. In contrast to a recumbent bicycle, where the upper body is more or less stationary while only the legs provide power, rowing bikes offer a much more complete workout.

There are solutions such as the Thys rowing bike, which employs a full rowing motion on a recumbent frame, but there remain particular issues that remain unaddressed. In particular, this project focuses on solving the problems associated with using a rowing bike in the urban environment: difficulty starting quickly, discontinuous acceleration, and instability on slippery or loose road surfaces. Another focus of the design is to create a rowing bike concept that can be manufactured at a low cost.

This project will evaluate the state of the art in rowing bikes and present a specific design concept that optimizes rowing bikes for urban environments. The resulting design will be a success if it is able to provide excellent mobility and exercise for its user while meeting the challenges -such as traffic, frequent stops, evading dangerous drivers- associated with biking in cities.



## **2 Project Goal**

The goal of this project is to investigate the feasibility of building a new form of urban transit rowing bike with these characteristics:

### **Main Functional Requirements:**

- Provide excellent exercise involving all muscle groups
- Price below \$1000
- Safe in a lateral skid
- Smooth and safe stop and start transitions
- As narrow as a normal bike
- Safe visibility to motorists
- Safe rider roadway visibility
- One day charge capacity

### **Desired Additional Features:**

- Assist for hills, increased acceleration and consistent torque
- Acceleration equal to the maximum for a sports compact
- Easy to store in currently available bike storage infrastructure

### **Design Philosophy:**

An overarching design philosophy guides this projects development. Key tenants are as follows:

- Minimize complexity to reduce cost
- Use new propulsion and layout to maximize performance
- Maximize novelty as a consequence

### **3 Background**

The background section is divided into three parts: one, a discussion of why human-powered vehicles will be more important in the future and some criteria that they will need to meet; two, a discussion of the physiology of exercise and the physics involved in rowing as a power mode; and three, an analysis of the ideal range of motion and geometry in rowing. This section is meant to establish the context within which urban human powered vehicles operate. The first contextual element, Need for Urban Transport, is also helpful for the design evaluation section.

#### **3.1 Need for Urbanization Transport**

Cities offer opportunities and infrastructure that are not available to rural communities; this is one reason that cities continue to grow. The developed and developing world is rapidly becoming more populous as people move into cities in order to participate in the opportunities that their density and connectivity offer. The year 2010 marks the first year that more than half of the world's population resides in an urban center and this trend is forecast to continue at a rapid pace. There are many problems that have arisen as a result of rapid urbanization and increased wealth, but one of the most striking and most costly is increasing congestion in automotive corridors. One solution to this problem is to transition to an urban transportation mix that focuses on bicycles rather than cars as the fundamental unit of point-to-point urban travel.

As cities grow they face increasing challenges in transportation. The automobile has thus far served as the underpinning of urban transport in the developed world, but, as populations grow, congestion increases threaten its utility. Almost every major city in the world loses billions of dollars per year in productivity to automobile congestion. This problem is also linked to the obesity epidemic which has it's own set of costs<sup>1</sup>. On the bright side, the Netherlands has proven that human power in the form of bicycles can be an irresistibly effective solution for urban congestion<sup>2</sup>. In order to begin the process of designing a human-

powered transportation system for cities in the US, it is important to evaluate the range that must be traveled.

### **3.1.1 Modes of Human Transport in Cities**

*Walking.* Walking is the basic form of human transportation by default. It requires no additional investment or resources and has the benefit of low-impact exercise which can improve health and productivity. The average person can walk at a speed of 2-4mph. If the maximum transit time for an individual is 30 minutes then the effective "transit radius" for walking ranges from 1-2 miles. In small and very dense cities, walking may be an appropriate means of transit but it falls short for the average city.

*Running and Jogging.* The range of running speeds are between 6 and 10 mph for an average adult in decent shape. This translates to a range of 3-5 miles. This distance is roughly half of what is required for effective urban transportation.

*Biking.* The average speed of a cyclist is 14/mph but can range up to nearly 30/mph for athletes. Assuming that there is limited improvement in average cycling speeds, the maximum route distance is 7 miles. This is a perfect fit for the urban radius that has been defined below.

### **3.1.2 Trends in Human Settlements**

One consequence of dense urban centers is that distances between routine destinations are reduced within the accessible range of human power. For the analysis of human power in American cities, it is first important to establish the minimum distance that must be traveled within an average city. Based on the US Census data ending in the year 2008, the average city in the US contains roughly 3 million people<sup>3</sup>. In order to cover more cities, we can double that number to 6 million for the purpose of this analysis. Now, we can use Boston,

MA as a representative city in order to approximate a typical worst-case (longest) trip distance. The radius surrounding the city of Boston can be roughly estimated by tracing the travel distance from the adjacent towns of Brookline to Somerville. The distance between these two points is the longest usual route from one point to another within the metro zone. This distance is 7 miles.

### **3.2 Health Benefits of rowing bikes (*Claudio*)**

The health goals are to provide a complete body workout for muscle building along with the best peak power and endurance.

Along with its cardiovascular benefits, rowing bikes simultaneously work more major **muscle** groups in the body than the traditional exercise forms of running or biking. Because of the constant rowing motion, deeper core muscles are also activated more effectively; **this** will improve a person's core strength and consequently a person's flexibility.

#### **3.2.1 Cardio principles**

Like cycling, an exercise rowing machine will improve cardiovascular fitness. For simple cardio health, a person should be working within an intensity anywhere between 60-85% of their target heart rate for at least 10+ minutes. For body fat loss, they should be active over a period of 25-30+ minutes [6]. The higher the intensity the exercise is, the more calories will be burned in one session in less time. In general, glycogen stores are used before reserved energy stores from fat are recruited in greater amounts. Usually, glycogen stores are not really being used up in aerobic activity for the body to induce a backup shift of using fat reserves until after around 25 minutes of aerobic **activity** at a specific intensity (60-85% target maximum heart rate). The higher the intensity **of** the aerobic activity is, **the** more likely it is to start using these reserves of energy.

### 3.2.2 Body Fat Loss efficiency

The trick to really 'burning calories' due to this kind of exercise will occur if a person is in repeated motion as specified by these guidelines: whatever the motivation to stay active on a UTRB for over a period of 25-30+ minutes at an intensity within at least 60 – 85% of a person's target heart rate zone will burn calories effectively. Anything less than that may not be functional. The higher the intensity, the more calories burned. The more calories burned, the more body fat **lost**.

Furthermore, because the UTRB is designed to recruit more muscles in the body to be used in an aerobic state than other forms of aerobic exercise, by the sheer laws of Thermodynamics, it will collectively burn more calories than other forms of aerobic activities, such as jogging or bicycling, even at lower intensities.

If the resistance of rowing the T bar is even greater than having to row the UTRB on any surface **inclined** greater than 0 degrees, in principle, the chances of developing muscle mass and strength **in** the target muscles being worked (as described in the next section of this report) will increase. This is because of the simple principle of hypertrophy occurring to **muscles** due to greater resistance.

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The reason to note this is because, ultimately, the more muscle mass a person has, the more calories they can burn during any activity [6]. **Therefore**, although the UTRB could be potentially used for strength training, as long as a person is rowing up an inclined plane within their limits (able to perform at most 10 -15 strokes before resting), the more intense the resistance for a greater endured period of time, the more calories will be burned.

### 3.2.3 Upper + Lower body, muscular, core, and stretching benefits

Specifically, the continual motion of rowing against a challenging resistance will work the core muscles of the body such as the hip flexors, the rectus abdominus, the transverse abdominus, the psoas major, adductor muscles, gracilis, pectineus, tensor faciae latae, and iliacus. The synergistic (secondary) muscles worked in the core are the serratus anterior muscles, and the internal and external obliques.

All these muscles are functional and essential in the kinetic chain of movement in one's body. The stronger and more resilient these muscles are, the more powerful and sturdy these muscles can be to generate a force. The better these muscles get developed, the more improved the skeletal posture of **any individual who** uses a rowing bike.

<<show this"when core muscles are in optimal condition and development, they force the other adjacent muscles in that area to stretch out to their ideal development and alignment. As a result, core training promotes greater flexibility for a person's body.>>

Furthermore, the UTRB will also help develop the following major muscle groups in the upper body: the latissimus dorsi, the rhomboids, the teres major, and trapezius. The synergistic muscles worked in the body that are not core muscles being worked due to the rowing movement will be the triceps, biceps, and quadriceps.

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### 3.2.4 Comparable Cardio benefits of Rowing vs cycling ergometry.

Rowing has shown that it supersedes cycling ergometry (power) in terms of peak power and VO<sub>2</sub> rates for endurance.

	Rowing	Cycling
Average maximal power (peak power)		higher (P less than 0.05)

VEBTPS (pulmonary ventilation where body temperature pressure is saturated)	higher during rowing graded exercise test	lower during rowing graded exercise test
VO2 STPD ( maximal oxygen consumption, maximal oxygen uptake or aerobic capacity under standard conditions for temperature and pressure )	higher during rowing graded exercise test	lower during rowing graded exercise test
HR (heart rate)	higher during rowing graded exercise test	lower during rowing graded exercise test

It should be noted that consistent linearity was reported to be found between VE (pulmonary ventilation) BTPS (body temperature pressure saturated) and VO2 STPD (standard conditions for temperature and pressure) and between HR and VO2 STPD for both exercises during the tests.

Results indicated that energy costs for rowing ergometry **were** significantly higher than cycle ergometry at all comparative power outputs, including maximum levels. As a result, rowing ergometry could be an effective alternative activity for physical fitness and exercise rehabilitation programs.<sup>4</sup>

### 3.3 Physics of a rowing bike (*Claudio*)

#### 3.3.1 Principle of operation (rowing bike)

The UTRB is a human-powered transportation vehicle designed with the principles of an exercise rowing machine, but modified with an attachment of pulleys that will induce



locomotion for the rowing machine **through its** connection to the three **affected** wheels below.&nbsp;

As the person starts the row, their feet should already be slipped into the pedals of the sliding platform that is attached to a rail, and their hands simultaneously holding onto a T shaped handle bar lever that arcs back and forth on a fixed point on the frame. As the person extends their arms forward (as is similar to the eccentric portion of a repetition movement in a rowing exercise), their legs are drawn into the core of their body as the platform slide should already be along the rail close to them.

To start the bike in locomotion, leading with their latissimus dorsi muscles, a person should hold onto the T bar hand rail and draw their arms to into the direction of the core of the body. The momentum of the force generated by the movement causes the riders body to recline onto the back rest of the seat while simultaneously the natural mechanics of the movement forces their legs to straighten out so that the sliding platform is now away on the other end of the rail.

<show this>

As this is done, the T bar has moved from one arc length to the other one as seen. There is a chord attached to the top right side of the handlebar called the **outgoing drive cable**. This cable is responsible for pulling the **rear wheel mechanism** piece that is attached to the rear wheel to turn clockwise against the ground for an estimated 2-3 radians. As this is happening, simultaneously, the **shift cable** will perform the same function on the rear wheel. However, positioning of the shift cable can improve the torque (and hence the assisted power) to go up hills. The further way the assisted cable is from the center of rotation of the rear wheel, the more torque will be created. At the same time, the shift cable is responsible for pulling the sliding platform away from the core of rider. That way their legs are extended at the end of the row.

There is a recoiling mechanism that will allow the tbar handle and sliding rail to return to their starting position. We considered a standard spring that would allow the T bar and sliding platform to upright themselves during every stroke. However, the pulling force on the Tbar needed for a person to draw that Tbar towards them that is caused by a spring resistance would be so great it would tax the riders energy too quickly to make for an efficient riding experience. The most logical replacement for a rope is as follows:

1) the shift and drive cables would be made of a bungee chord that would assist bringing the T bar back. As they stretch, the properties that make the material would cause the bungee to recoil back. The interior of any traditional bungee chord is a rubber material. The outside casing of it is an cross hatched interwoven polyester fiber, which allows it to be resilient to tearing but can spread apart as well. When stretched, the cross hatched interwoven fibers can stretch but at the same time provide protection to the rubber and thus add the proper strength to the chord.

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<<calculate the effect>>

2) the angle of the sliding platform and of the rail. Due to an elevated angle for the sliding platform (about 15 degrees) existing on the rail, the force of gravity itself will allow the footpad to slide towards the direction of the seat. However, added to this fact that their feet are attached to the elevated rail, the very weight of a riders legs will cause the footpad to slide with even less difficulty and make them draw into the core of the riders body as well.

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What this means is that only the concentric (rowing) portion of the repetition is really creating resistance against the major targeted muscles groups of the body used to accomplish a row, and the eccentric (restoring) portion of the repetition is not depleting a rider of much energy. The small segment of time of rest (during the eccentric portion of the repetition) is just enough to allow a person to restore their ATP stores [5] and catch their breath while still inducing an aerobic state on the body.

These two cables (the outgoing cable line and the shift cable) are the two cables primarily responsible for the recoil mechanism on the bike and specifically (the shift cable), the control determining gears and torque assistance for the rider.

### 3.3.2 Energy Conversion

**+ maximum energy output (top speed, 30% grade, max power assist)**

On average, the maximum amount of energy output that a human can induce from rowing is about 35 strokes per minute (SPM). We demonstrate the physics of how at this near maximum state of constant rowing, the amount of energy and power can be calculated.

### 3.3.3 Max and Min distance

**in a given time period OR time given a distance.**

Using the principles as stated in the previous section, we offer the mathematics on how to calculate the energy and power output for certain ranges of SPM cycles yield.

## 3.4 Optimal Angles (*Claudio*)

The mechanisms behind rowing consists of inversely drawing in the extended limbs to the core upon every stroke. The most optimal angle the rail and seat should be positioned that

allows a rider to work every muscle homogeneously for greater lengths of time is actually with minimum elevation of the rail or seat. The reason for this as it turns out, is that any change in elevation of either the rail or seat may benefit developing certain muscles, but unfortunately will eventually cause these muscles to develop lactic acid buildup quicker, thus causing the rider to have to stop and rest more frequently between rounds.

When a muscle is used to work against a certain resistance, it will contract in a flexion and back to an extension position, and indirectly this activity in any muscle group can assist in allowing the larger system as a whole (the human body) to exert some type of force to perform physical work. If the resistance is too great (suppose 6 to 10 repetitions of flexion and extension of that muscle are obtained before the rider can not move that muscle any more due to lactic acid buildup in that muscle), the rider may benefit from a great hypertrophy workout but in terms of functionality, only be able to use the rowing machine to move short distances [1]

[5](#)

If the seat of the rowing bike is raised at any higher elevation than a few degrees, the muscles in the lower abdomen, and hip flexor complex will be used up more effectively. There is a negative consequence to this: the higher the seat is elevated, the quicker these muscles will tire.

If the rail itself is elevated so that the feet upon sliding elevate at a higher angle, the muscles in the lower back and upper rectus abdominal muscles will sustain a great workout, but tire out quicker.






The only benefit to having an adjustable elevated seat mechanism and rail is simply preference: The preference of targeting certain muscles more effectively such as the lower abdomen and hip flexors with elevated seat and the upper abdominal muscles and lower lat/back area with an elevated rail.


#### 4 State of the Art

There is substantial diversity among modern bicycle designs and the following is an attempt to catalog the major categories along with detailed examples from important classes. Each item identified in this state of the art will be supported by an explanation describing its key features and associated benefits. The final element of each item is a subjective assessment of performance rated 1-10 followed by a rough measure of complexity; the final filter is based on how novel and compelling the design is. These numbers will be helpful quantitative guides in subsequent design decisions.

##### 4.1 Common Types of Urban Bicycles

Bike Type	Image	Unique Properties
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<p>1. Single Speeds</p>	 <p>Image Source: <a href="http://www.mapmyride.com/community/groups/683124160812266427">http://www.mapmyride.com/community/groups/683124160812266427</a></p>	<ul style="list-style-type: none"> <li>• no gear shifter</li> <li>• conventional road frame</li> <li>• flat handle bar</li> <li>• with or w/o fixed gear</li> <li>• with or w/o brakes</li> <li>• Most popular type</li>   <li>• Price: \$800-\$1,000</li> </ul>
<p>2. Used 'vintage' road bikes</p>	 <p>Image Source: <a href="http://www.vintage-trek.com/Trek_galleryKM.htm">http://www.vintage-trek.com/Trek_galleryKM.htm</a></p>	<ul style="list-style-type: none"> <li>• 10 Speed and up</li> <li>• Steel frame construction</li> <li>• Very popular</li>   <li>• Price: \$250-\$400</li> </ul>
<p>3. Cruiser Bikes</p>	 <p>Image Source: <a href="http://ab-bike.com/info_steel-city-bike.html">http://ab-bike.com/info_steel-city-bike.html</a></p>	<ul style="list-style-type: none"> <li>• Designed for style</li> <li>• Upright seat position</li> <li>• Larger diameter tires</li> <li>• Heavy frame</li>   <li>• Price: \$500-\$700</li> </ul>

<p>4. Electric Bike (e-bike)</p>	 <p>Image Source: <a href="http://www.china-ebikes.com/en/Products.asp">http://www.china-ebikes.com/en/Products.asp</a></p>	<ul style="list-style-type: none"> <li>• Electric Motor</li> <li>• Battery</li> <li>• Power Controller</li> <li>• Top speeds 25mph</li> <li>• 30M in China</li> <li>• Price: \$650 (estimate)</li> </ul>
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The price range for the most common urban bicycles is \$500-\$800, while used or 'vintage' bikes can run as low as \$250. In order to charge a higher price, an alternative product would need to have impressive advantages over traditional systems. One advantage of common urban bikes is that they are very narrow. These bikes are all able to fit easily in narrow bike lanes, be stored at bike-racks and on sidewalks, and slip between cars in traffic. The narrow track of these bikes is a major benefit. The final criterion that makes these bikes valuable is that they are very maneuverable, because riders can bob and jive their center of mass in order to avoid obstacles. This flexibility is one of the reasons that it is possible for experienced riders, for example, to balance on two wheels while waiting at a stop light. Although cyclists who can balance are able to start more quickly than other riders, even riders who are unable to balance at a stop can get a rolling start by pushing off the ground prior to the first stroke. This initial velocity is helpful because it allows the rider to make course corrections to prevent tipping over immediately following the start.

The primary drawbacks to all of the common bike types are that they do not provide full-body exercise, and that they have a complex gearing system that can degrade in the elements. As with all bikes, there is a maximum amount of power that can be delivered to the wheels

because the rider is not able to push against anything aside from his/her body weight. Despite these drawbacks, these bikes are the state of the art for urban human-powered vehicles and, as a mode of transit, they are on the rise in major cities from Boston to Shanghai.



## 4.2 Alternative Bicycles for Transport



Alternative Type	Image	Key Properties
5. Traditional Recumbent	 <p>Image Source: <a href="http://teacherontwowheels.com/2008/06/06/recumbent-riding/">http://teacherontwowheels.com/2008/06/06/recumbent-riding/</a></p>	<ul style="list-style-type: none"> <li>• Long chain drive-train</li> <li>• Efficient power delivery</li> <li>• difficult to start</li> <li>• Price: \$1,000</li> </ul>
6. Covered "Streamlined"	 <p>Image Source: <a href="http://www.wired.com/culture/lifestyle/news/2007/03/bikerecord_0330">http://www.wired.com/culture/lifestyle/news/2007/03/bikerecord_0330</a></p>	<ul style="list-style-type: none"> <li>• Speed record (81mph)</li> <li>• Straight, flat roads only</li> <li>• Can't start without helpers</li> <li>• Cost: \$2,000</li> </ul>
7. Two Front Wheels ("tadpole" Trike)	 <p>Image Source: <a href="http://www.utahtrikes.com/TRIKE-CTVILLAGER.html">http://www.utahtrikes.com/TRIKE-CTVILLAGER.html</a></p>	<ul style="list-style-type: none"> <li>• Stable in slippery conditions</li> <li>• Easy to start from stop</li> <li>• Price: \$1,600</li> </ul>
8. Two Back Wheels ("delta" trike)		<ul style="list-style-type: none"> <li>• Can tip while breaking in turns</li> <li>• Bulky</li> <li>• Price: \$350</li> </ul>

	Image Source: <a href="http://www.besportier.com/archives/gomier-electric-powered-tricyc.html">http://www.besportier.com/archives/gomier-electric-powered-tricyc.html</a>	
9. Velomobile (car-cycles)	 <p>Image source: <a href="http://www.velomobiles.net/buying/buying.html#vmnl">http://www.velomobiles.net/buying/buying.html#vmnl</a></p>	<ul style="list-style-type: none"> <li>• Covered 3 wheeler</li> <li>• 2 front wheels</li> <li>• Higher speed than open version</li> <li>• difficult to enter-exit</li> <li>• Price: \$4,000-\$10,000</li> </ul>

In contrast to the most common urban bikes, recumbent and high-performance three-or-more wheeled bikes are much less common and more expensive. The market for these vehicles is mostly contained within the recreational sector, although some people use these vehicles for commuting. Each alternative type of vehicle listed above has a unique set of advantages and disadvantages. Far and away the biggest drawbacks are price and basic compatibility with urban situations like frequent stops and narrow bike lanes.

#### 4.3 Tilting with 3 or more wheels

Tilting Bike Name	Image	Key Properties
10. Tripendo HPV <sup>6</sup>	 <p>Image Source: <a href="http://www.tripendo.com">http://www.tripendo.com</a></p>	<ul style="list-style-type: none"> <li>• Hand lever tilting</li> <li>• Hand lever steering</li> <li>• Carbon Mono-body</li> <li>• 4 bar suspension lineage w/ tilting mechanism</li> <li>• Full-size wheels</li> </ul>



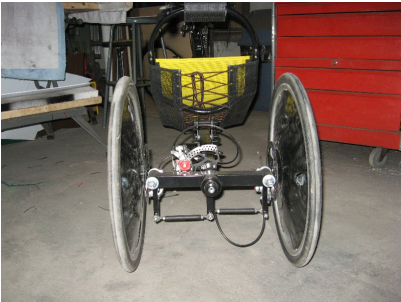
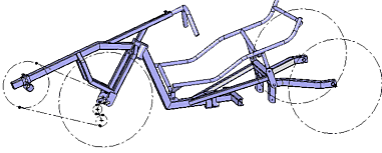



		<ul style="list-style-type: none"> <li>• Price: \$3,000 (and up)</li> </ul>
<p>11. Munzo TT<sup>7</sup></p>	 <p>Image Source: <a href="http://www.fastfwd.nl/">http://www.fastfwd.nl/</a></p>	<ul style="list-style-type: none"> <li>• Rear swing-arm tilting</li> <li>• Single suspension shock</li> <li>• Composite rear wheels</li> <li>• <i>Width no wider than rider</i></li> <li>• Detachable front section</li> <li>• Price: \$2,000 (estimate)</li> </ul>
<p>12. Apex hydraulic</p>	 <p>Image Source: <a href="http://apax.ca/">http://apax.ca/</a></p>	<ul style="list-style-type: none"> <li>• Extraordinarily smooth</li> <li>• Heavy/complex hydraulics</li> <li>• Narrow Width</li> <li>• Price: \$3,000 (estimate)</li> </ul>
<p>13. Black Max</p>		<ul style="list-style-type: none"> <li>• Very fast cornering</li> <li>• Like Munzo TT but with parallelogram linkage.</li> <li>• No suspension</li> </ul>

	Image source: <a href="http://www.fleettrikes.com/blackmax.htm">http://www.fleettrikes.com/blackmax.htm</a>	<ul style="list-style-type: none"> <li>• Price: \$1,000 (estimate)</li> </ul>
14. Jet Trike	 Image Source: <a href="http://jetrike.com">http://jetrike.com</a>	<ul style="list-style-type: none"> <li>• Integrated tilting and leaning design</li> <li>• No suspension</li> <li>• Open-Source Design</li> <li>• Price: \$1,000 (estimate)</li> </ul>

These tilting trike designs are unique because they blend the stability advantages of three-wheeled models with the performance and lighter construction of two-wheeled models. In the case of the Tripendo and the Apex, the performance of each is unique, including very agile turning response and smooth riding on stairs, respectively. The Munzo TT design is very simple, light, stable and narrow, effectively blending the positive aspects of bikes and trikes but without any *new* abilities. In order to create a tilting trike that is cost-competitive with incumbent urban bikes, it is most important to identify simple solutions with few parts. The Munzo TT design fits this description and its novelty (only 2 instances were found) make it a very interesting technology. The Black Max design is also unique and offers very high performance and low complexity but lacks a suspension system; a second drawback is that there is no easy place to mount motors.

#### 4.4 Rowing Bikes

Rowing Bike Name	Image	Key Properties
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<p><b>15. Thys Rowing Bike</b></p>	 <p>Image Source: <a href="http://rowingbike.com/site/EN/">http://rowingbike.com/site/EN/</a></p>	<ul style="list-style-type: none"> <li>• Stationary Center of Gravity</li> <li>• Lines don't rust and last longer</li> <li>• Unique spiral pulley gearing system</li> <li>• Steering &amp; rowing combined in handlebar</li> <li>• Price: \$4,400<sup>8</sup></li> </ul>
<p><b>16. Rowbike</b></p>	 <p>Image Source: <a href="http://www.rowbike.com/">http://www.rowbike.com/</a></p>	<ul style="list-style-type: none"> <li>• Sliding seat, large rider movement</li> <li>• Chain based drive-train</li> <li>• Foot steering</li> <li>• Price: \$1,200<sup>9</sup></li> </ul>
<p><b>17. Scull Trek<sup>10</sup></b></p>	 <p>Image Source: <a href="http://www.sculltrek.sk/images/foto/image%20%2816%29.jpg">http://www.sculltrek.sk/images/foto/image%20%2816%29.jpg</a></p>	<ul style="list-style-type: none"> <li>• Single Speed, Pulley Drive</li> <li>• Sliding seat and mass</li> <li>• Hand steering</li> <li>• Price: \$1,800</li> </ul>

18. VogaBike<sup>11</sup>



Image Source: <http://vogabike.com/>

- Cable-chain hybrid
- Stationary rider mass
- Complex pulley and linkage power delivery
- Price: \$2,000 (estimate)





Image Source: <http://www.greatoutdoors.com/published/rowing-the-other-paddle-sport>



The rowing motion employed on a scull is the inspiration for each of the above designs. The most important difference among the designs is whether the rider's body or limbs are in motion. For the Rowbike and the Scull Trek the body of the rider oscillates back and forth in the same way that an actual scull operator does. This approach has the major disadvantage of making vehicle handling characteristics unpredictable. An additional disadvantage is that the rider's body mass causes much of the energy to be used without adding to locomotion. The principle difference between the VogaBike and Thys RowingBike is that the former employs a chain and traditional bike transmission while the latter utilizes an original 100%



pulley and line drive. The Thys drive-train is simpler, lighter and proven to be more durable than chain-based drive-trains, and is thus superior.

#### 4.5 Power Assist

Power Assist Name	Image	Key Properties
18. Green Wheel <sup>12</sup>	 <p>Image Source: <a href="http://www.altwatch.com/green-wheel-the-future-of-electric-bikes/">http://www.altwatch.com/green-wheel-the-future-of-electric-bikes/</a></p>	<ul style="list-style-type: none"> <li>• Integrated Single Unit (motor, battery, controller)</li> <li>• Lower Performance</li> <li>• Cost: \$350 (estimate)</li> </ul>
20. Geared System	 <p>Image Source: <a href="http://pedaleconomics.blogspot.com/2006_10_01_archive.html">http://pedaleconomics.blogspot.com/2006_10_01_archive.html</a></p>	<ul style="list-style-type: none"> <li>• Highest Power</li> <li>• No added rolling mass</li> <li>• Design flexibility</li> <li>• More moving parts (chain, gear)</li> <li>• Cost: \$400-\$1000</li> </ul>


<p>21. Hub Motor</p>	 <p>Image</p> <p>Source: <a href="http://www.electricbikeshed.co.uk/shop/electric-bicycles/oxygen-bikes/oxygen-imate-explorer.html">http://www.electricbikeshed.co.uk/shop/electric-bicycles/oxygen-bikes/oxygen-imate-explorer.html</a></p>	<ul style="list-style-type: none"> <li>• Simple power delivery</li> <li>• Rolling mass added</li> <li>• The price is trending down w/ scale mfg.</li> <li>• Cost: \$500</li> </ul>
<p>22. Two Stroke Engine</p>	 <p>Image Source: <a href="http://www.zbike.com.au/about-z-bikes.htm">http://www.zbike.com.au/about-z-bikes.htm</a></p>	<ul style="list-style-type: none"> <li>• Loud in operation</li> <li>• Complex engine</li> <li>• Range extension with larger tank</li> <li>• <i>New version of the mo-ped</i></li> <li>• Cost: \$600-\$1000</li> </ul>

These power assist systems are generally costly as aftermarket products. The integrated systems as seen in section 4.1 are mass-produced and made cheaper by using lead-acid batteries instead of lithium-based solutions. Lead-acid batteries are cheap, however producing them causes lead waste and pollution.

One important difference between electric motors and gas engines is the torque curve response. Electric motors are able to deliver full torque even at zero RPM while gas engines develop torque only at high angular velocity. One advantage of using an electric power assist is that it can improve acceleration in traffic and provide for a safer and more responsive vehicle in the heavy traffic of cities. Geared systems and hub motor configurations keep the motor, battery, and controller separate and thus each component can be larger and more powerful. It is for this reason that one of these two options is probably the best for urban transport.



#### 4.6 Next Best Powered Designs


Design Name	Image	Key Properties
<p>23. CarCycle</p>	 <p>Ann and Robin Sorenson ride the Car-Cycle in a strong cross wind.</p> <p>Image Source: <a href="http://microship.com/bobstuart/carcycle.html">http://microship.com/bobstuart/carcycle.html</a></p>	<ul style="list-style-type: none"> <li>• Integrated carbon-fiber suspension</li> <li>• Indicator fin</li> <li>• large cooling vent</li> <li>• power assist</li> <li>• Non-tilting trike</li> <li>• Price: \$4,000 (estimate)</li> </ul>

The CarCycle is unique among human-powered vehicles because it incorporates a number of features of a car in an elegant package. This design incorporates a complete enclosure, ample enclosed storage capacity for groceries or a child, a unique indicator fin, complete signal lights, electric power assist for hills and a light-weight composite sub-frame. In it's day this design was among the best velomobiles and demonstrated a number of unique technology concepts that are relevant for all human-powered urban transit designs. It was never produced for lack of funding and fleeting public interest.

<p>24. RunAbout Cycles</p>	 <p>Image Source: <a href="http://www.electric-cycle.com/html/runabout_0.html">http://www.electric-cycle.com/html/runabout_0.html</a></p>	<ul style="list-style-type: none"> <li>• Large electric power system</li> <li>• Heavy wheels designed for downhill MTN bike racing</li> <li>• Heavy 2.5" heavy-duty tires</li> </ul>
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		<ul style="list-style-type: none"> <li>• Robust steel frame</li> <li>• Non-tilting trike</li> <li>• Price: \$6,000</li> </ul>
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RunAbout Cycles has been a successful small company producing a high-performance powered trike that is safe in the traffic of a small-sized city because of its robust construction and high power. This bike is capable of rapid acceleration at stop lights and, since it doesn't tilt, is very stable and maneuverable. The primary drawbacks are that it is very heavy and expensive on account of its robust construction and high power. The RunAbout Cycles trike is unique among powered trikes in that it has been a commercial success.

25. Tripendo w/ motor kit	 <p>Image Source: <a href="http://tripendo.com/">http://tripendo.com/</a></p>	<ul style="list-style-type: none"> <li>• Tilting tadpole design</li> <li>• Independent suspension</li> <li>• 3x 26" Wheels</li> <li>• Lever tilt &amp; steering control</li> <li>• Tilting trike</li> <li>• Price: \$6,000</li> </ul>
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The motorized Tripendo is a very elegant and agile machine despite the complexity of its design. By employing independent tilting and steering controls the bike is capable of quick turns that are not possible with a 2 wheeled alternative. The powered Tripendo is wider because it utilizes the 'tadpole' layout configuration but this also makes it more stable and safer. As with the other two top designs, the Tripendo with power assist is many times the budget of a typical urban cyclist and is unlikely to ever become a widely-used mode of urban transport.

Each of these powered three-wheeled designs are very effective in the context of the design objectives and applications for which they were built. Since this project is to design a rowing bike, there is clearly a wide gap between the best cycle concepts and the best rowing bike.

#### 4.7 Select Sub-system Technology Review

The prior sections have described the prior art in on an individual basis. The following table is a comparison of several important subsystems to provide additional clarity to the analysis of the gap between existing technologies and an *idealized* design.

Sub-System Technology One	Sub-System Technology Two
<p>Tilting Tadpole Trike:</p> <ul style="list-style-type: none"> <li>• Very stable</li> <li>• Simple chain drive geometry</li> <li>• complex tilting geometry</li> <li>• complex suspension</li> </ul>	<p>Tilting Single Front-wheel Trike:</p> <ul style="list-style-type: none"> <li>• Less stable in unexpected lateral slides</li> <li>• More aerodynamic potential</li> <li>• Can be made to be narrow</li> </ul>
<p>Parallelogram Tilting Geometry:</p> <ul style="list-style-type: none"> <li>• Smaller vertical dip</li> <li>• Deep tilting angles possible</li> <li>• Complex suspension design is expensive</li> </ul>	<p>Swing-Arm Tilting Geometry:</p> <ul style="list-style-type: none"> <li>• Larger vertical drop in turns requires careful design</li> <li>• Swing-arm length limits maximum tilting angle</li> <li>• Wheelbase widens in turns</li> <li>• Very simple suspension design, proven</li> </ul>
<p>Cycling:</p> <ul style="list-style-type: none"> <li>• Well-established technology</li> </ul>	<p>Rowing:</p> <ul style="list-style-type: none"> <li>• Simple cable-pulley drive</li> </ul>

<ul style="list-style-type: none"> <li>• Smooth power delivery for acceleration</li> <li>• Leg-only exercise, esp. for recumbent</li> </ul>	<ul style="list-style-type: none"> <li>• Discontinuous power delivery</li> <li>• Full-body workout</li> </ul>
<p>Tilting Trike:</p> <ul style="list-style-type: none"> <li>• More comfortable at speed</li> <li>• Lighter components</li> <li>• Requires more rider skill</li> <li>• Can be narrow at slow speed</li> </ul>	<p>Static Trike:</p> <ul style="list-style-type: none"> <li>• Fail-safe construction</li> <li>• large bending moments induced while cornering require heavier construction</li> <li>• Wide frame required</li> </ul>
<p>Two Dimensional Frame:</p> <ul style="list-style-type: none"> <li>• Automated manufacturing</li> <li>• Fewer manufacturing operations</li> <li>• Can use composite materials which are getting better over time</li> </ul>	<p>Aluminum, Titanium or Steel Tube Frame:</p> <ul style="list-style-type: none"> <li>• Requires a number of welding steps</li> <li>• Good structural welds require expensive expertise</li> <li>• Metals are finite and in high demand for buildings, aircraft, trains and will become more costly in time.</li> </ul>
<p>Chain-Motors:</p> <ul style="list-style-type: none"> <li>• Large motors can be used</li> <li>• Motor mass closer to vehicle center</li> <li>• Many models and vendors</li> </ul>	<p>Hub Motors:</p> <ul style="list-style-type: none"> <li>• Theoretical design</li> <li>• Simple and can become cheap</li> <li>• Easily integrated with any final design</li> </ul>
<p>Separate Batteries:</p> <ul style="list-style-type: none"> <li>• Large energy storage possible</li> <li>• Easy to replace older batteries</li> <li>• High energy flow possible</li> </ul>	<p>Hub Batteries:</p> <ul style="list-style-type: none"> <li>• Limited total energy storage</li> <li>• Limited energy flow rate</li> </ul>



## 5 Gap Identification

This discussion will assume the starting point of the Thys Rowing Bike design as the most mature and refined art in the rowing bike category.

### 5.1 Rowing Bikes

The variety of bikes present different solutions for specific contexts. Rowing bikes were developed primarily in the context of exercise and recreation and although they meet their desired intent they fall short as effective urban transportation. The following is a list of aspects that must be improved.

- 2 wheeled configuration is not safe for start from a red light (see tilting)
- Discontinuous power delivery causes irregular handling in hills and while accelerating
- Instability on slippery surfaces causes crashes which result in visibly scrapped thighs of Thys racers
- The drive system requires the design of a unique spiral pulley which drives up cost
- The high tolerances required to build the track system employed in Thys increases the cost
- Aluminum construction requires welding and human time, true throughout the bike industry. Companies are able to employ robotic welding equipment only after reaching high volumes.
- The foot pulley is complex because it needs to be large so that it can double as a spool in the gearing system. This is another component that must be custom made with high tolerances.

## 5.2 Tilting Trikes

In order to address the instability of rowing bikes like Thys, a tilting trike layout is desired. Tilting trikes present the unique features of being stable like a car while leaning into corners like a bike and have been developed primarily for recreation and as a technical hobby. Although the state of the art in tilting trikes is impressive and several have won awards the following items must be addressed in the urban context.

- Tilting trikes are very expensive due to their complex and use of custom parts
- The Munzo TT design employs a simple linkage but requires many welded joints and would therefore require many unique manufacturing operations which is intrinsically costly.
- The Munzo TT design is too low to be safe in the city although this increases it's speed. If the seat is configured in more of an upright position this issue would be taken care of.

## 5.3 Gap to the main functional requirements

High-quality exercise	Thys and all rowing bikes
Price under \$1000	urban bikes and traditional trikes (#8) only
Safe in a lateral skid	All tilting trikes and 'tadpole' trikes
Smooth and safe stop and start transitions	All trikes
As narrow as a normal bike	All 2 wheeled and only 'delta' tilting trikes
Visible to all motorists	Urban bikes, all others with signal flag mounted
Safe roadway visibility	All art except the very low: #6, 7, 11, 13, 14
Full day of charge	RunAbout Cycles, Tripendo Electric

We will use some of the characteristics of rowing bikes, tilting recumbent trikes and power assist systems and integrate them in a way that will best suit our specific application and context, namely the urban transportation environment.



## 6 Proposed Design

The previous sections of this report have been dedicated to evaluating the landscape of human powered transport in cities and different types of bicycles that have been created. Despite the fact that many bike designs were omitted there are still 25 very unique bike types documented in this report. The sheer volume of prior art presents an opportunity to recombine all of the best ideas into a single (better) design.

### 6.1 Vehicle Concept Evaluation

- Munzo TT + Thys Drive + Single Speed + Flat Composite Construction + Power Assist
  - This design is far and away the most simple and thus can be the most cost-effective. It can also be made to be very light weight by integrating the seat with the frame structure
- Thys spiral CVT + Munzo TT + Thys Drive + Power Assist
  - This is a close contender but for the sake of cost savings it should be eliminated from the design and it's function replaced by a more robust power assist that can quickly accelerate the vehicle to cruising speed.
- Tripendo + Thys + Single-Speed + Power Assist
  - Great handling but complex and wide
- Rowing recumbent with training wheels that descend in turns and at low speed
  - poor take-off acceleration, complex operation, failure risk
- Low tadpole trike + electronic power assist + wrap-around seat (T-Rex)
  - heavy and wide
- Long tilting arms in the front + rear wheel drive + rear wheel tilting + rowing drive
  - complex and heavy front end
- Tilting front and flat back section with smaller tires
  - this design would need to be heavy to be safe in turns

- Hydraulic drive + Thys rowing + Electric assist
  - Hydraulics are heavy and inefficient
- Thys drive + Electric Assist + Hydro-pneumatic suspension & tilting + Munzo TT seat/wheel/handle geometry
  - This concept is promising although the hydraulic tilt control components are not mature and, on the basis of pictorial analysis alone, appear to be heavy industrial hydraulic components. From the video

## 6.2 Final Design Concept

The following is the list of features that embody the best ideas from other attempts combined into one vehicle.

- A. Thys Rowing Bike geometry (Stationary rider, pulley and line based drive train)
- B. Munzo TT, rear swing-arm tilting system and integrated suspension
- C. Front wheel drive using line-pulley assembly inspired by the Thys Rowing Bike
- D. The rear wheels are driven from two independent electric motors. This configuration allows each rear wheel to provide power to accelerate while in a turn when each wheel must have a different angular velocity.
- E. Single-speed line-pulley configuration (to reduce complexity & cost)
- F. Fiber (carbon/glass) composite main structure with aluminum fittings. Instead of welded steel or aluminum segments that are only -strong enough if welded by experts-- the frame can be made as a single piece of high strength composite. If the design utilizes a flat frame concept where the frame is laser cut and assembled using standard fillers and fasteners then the front rail support, seat and all of the mounting pints for other parts can be made to be light and inexpensive. In time, composite materials will become increasingly cost effective as new carbon-based materials are invented. In the case of metal frames, the base metals are a scarce commodity and will only become more expensive in a world with increasing population.

- G. Externally sourced power assist (2x0.5hp motor-10lb, large battery-10lbs, power controller)
- H. All breaks, fasteners, cables, tires and other parts not mentioned are standard bicycle parts
- I. Signal tower like the CarCycle but with a rear and forward mounted camera similar to modern cars

**Core Requirement Review**

High-quality exercise	A, Full body rowing exercise
Price under \$1000	B, C, E & F, aim to reduce cost
Safe in a lateral skid	B, the tilting trike is stable without traction
Smooth and safe stop and start transitions	B, since Munzo TT is a trike geometry
As narrow as a normal bike	B, Munzo TT is very narrow
Visible to all motorists	I, Signal tower improves visibility at night and during the day
Safe roadway visibility	I, Cameras mounted on the signal tower improved long-range visibility
Full day of charge	G, power assist sizing to match this requirement

**Supplemental Requirement Review**

Power assist for hills & consistent torque	This is provided because larger motors and batteries were chosen instead of multiple gears. This also satisfies the design philosophy of reduced complexity
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Acceleration equal to the maximum for a sports compact	The choice to utilize a larger power plant means that the vehicle has very high rates of acceleration and traditional bikes with similar power accelerate faster than most cars
Easy to store in currently available bike storage infrastructure	The use of the Munzo TT tilting linkage results in a reduced width so that the vehicle can fit on standard bike paths. The fact that it is a 'delta trike' with only one wheel makes it compatible with the established infrastructure of bike racks.

### 6.3 Discussion of Key Features

Before delving into the detailed design and prototyping specifications for this project it is important to review several key features features of the design such as the approximate sizing, rowing operation, tilting method and power assist sizing.

#### 6.3.1 Approximate Sizing and Overall Dimensions

The Tripendo, Munzo TT and Thys Rowing Bike were all designed for riders of average size and weight because each are intended for public use. In the case of the Tripendo, the maximum rider weight is specified at 120kg (265lb) and height of between 5.5 feet and 6.5 feet. These rider characteristics conform to the average sizes and weight of people in the US and can be used to evaluate the approximate size of the UTRB vehicle. The ideal production process will accommodate for custom sizing each bike to fit it's intended user precisely<sup>13</sup> but for the purposes of an overall analysis the above assumptions will be used.

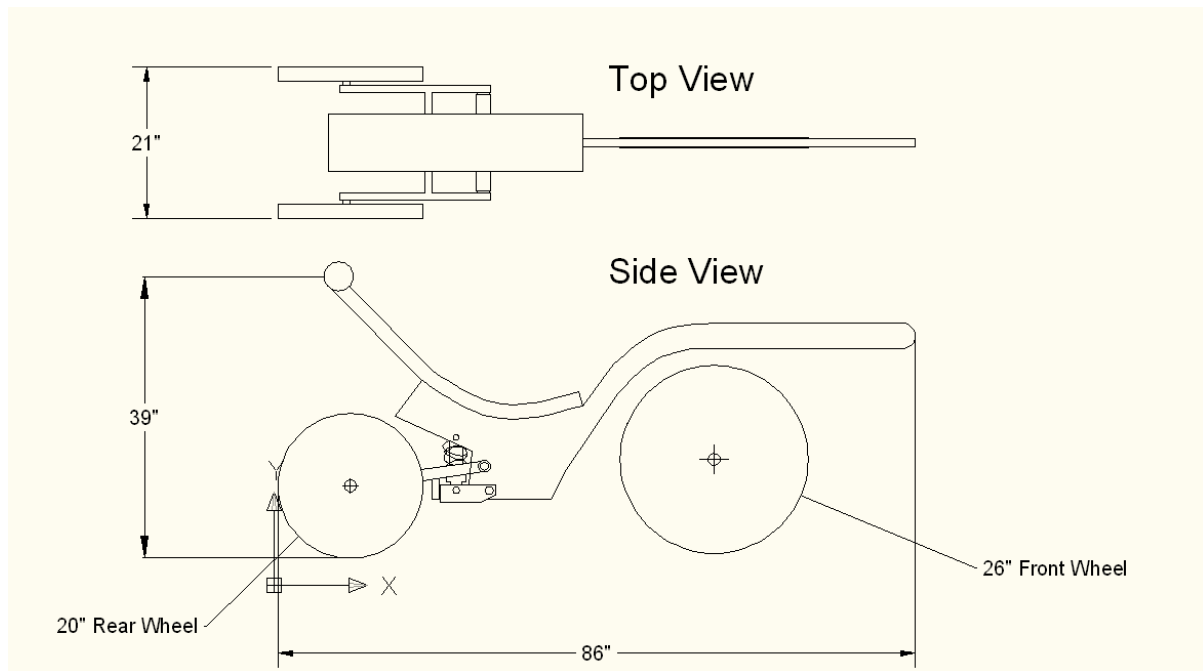


Image Source: Own Work

The overall dimensions of the UTRB will fall within the range of existing recumbent bikes while being somewhat slimmer than recumbent trikes such as the Tripendo (see reference figure I). The Tripendo has the following specifications: 86 x 39 x 34 inches. This vehicle will have the same overall length of 85 inches (7.2 feet) and a seat height no higher than 39 inches (3.25 feet). As a point of reference, the original 1960s mini cooper is a very small car and is 4.4 feet tall (see reference figure IV).

Although the Tripendo is high enough to be operated safely in traffic with a head height over 3.25ft, the Munzo TT is too low to see or be seen at roughly 2.5ft. The advantage of having a lower head position is a lower cross-sectional area and reduced bike drag. In order to take advantage of the reduced drag of the Munzo TT while providing adequate safety and visibility like the Tripendo, a signal tower must be implemented. The CarCycle employed a similar signaling method and somewhat demonstrated the feasibility of such a solution. As a matter of approximate sizing of 3.25ft will be used because it represents an upper limit for the vehicle's drag and material stress. Both of these upper limits are important when evaluating other facets of the design.

The ideal width of the vehicle would mirror that of the Munzo TT of roughly 16 inches (1.3 feet) because it is very slim while being stable fully tilted (see reference figure II). In order to make the design consistent with the above assumption that the vehicle will be scaled up by the same factor in order to maintain the same relative geometry. The following calculation is used  $(3.25\text{ft}/2.4\text{ft}) * 1.3\text{ft} = 1.75\text{ft}$ . This new dimension will be used to approximate material requirements among other elements.

The wheel dimensions required to operate the Munzo TT design are 20 inches in diameter and require the use of standard road tires for that same size (see reference figure III). The drawback to smaller wheel diameters, in contrast to the 26 inch standard for road bikes, is that they provide a bumpier ride while they are stronger and can hold up to harsher road conditions. In contrast to most road bikes, the UTRB employs a suspension system in order to absorb these shocks and there should be no net increase in ride roughness due to the smaller tire diameter employed. As a comparison, the Vespa scooter has 10 inch wheels and is used heavily for urban transport which further supports the idea that 20 inch wheels are perfectly adequate.

### Section 6.3.1 Reference Figures

I) Tripendo side view for height reference



Image Source: <http://www.tripendo.com>

II) Munzo TT rear view for width reference



Image Source: <http://www.fastfwd.nl>

III) Munzo TT side view for wheel size reference



Image Source: <http://www.fastfwd.nl>

IV) Early Mini Cooper for height reference



Image Source: <http://en.wikipedia.org/wiki/Mini>

### 6.3.2 Rowing System

The Thys rowing geometry is unique among rowing bikes because it contains no chains and maintains a stationary rider center of mass. The Thys rowing drive-train has two important elements: one, the forward block and pulleys or 'foot swagger'; and two, the spiral drive pulley mounted to the drive wheel or 'Snek'.

#### Front Assembly (see figure I)



The *foot swagger* has two main functions in the most recent design of the Thys drive-train.

The first function is to incorporate power developed from the motion of the arms and the motion of the legs into a single cord. This is accomplished by converting the linear motion of the arms and legs into rotational motion on a single axle and then converting the result back to linear motion. In this way the work done by the arms and legs is added without requiring that both actions happen at the same time or that they have the same travel. The second purpose of the *foot swagger* is to store or spool excess drive-line which is used to operate vehicle gearing.

### Rear Assembly (see figure II)

The rear assembly utilizes extra cord that is stored in the *foot swagger* system in order to move line onto and off of a specialized spiral drive pulley. By moving the excess cord back and forth between the rear *Snek* and the *foot swagger* a rider is able to change the active diameter of the drive pulley. More precisely, as more cord is spooled onto the *Snek* the drive cable is forced to climb further along it's windings and this means moving into a wider diameter region of the spiral pulley. The exact workings of the clutch mechanism that makes this spooling in and out possible are less complex than a traditional bike derailleur making the whole gearing concept a very elegant.

### Thys Rowing Bike Drive-Train Figures

I) Thys Front Assembly	II) Thys Rear Assembly
	
Image Source: <a href="http://rowingbike.com/site/EN/Models/Thys-222-Revolver/pnCurrent:2/">http://rowingbike.com/site/EN/Models/Thys-222-Revolver/pnCurrent:2/</a>	Image Source: <a href="http://rowingbike.com/site/EN/Models/Thys-222-Revolver/pnCurrent:3/">http://rowingbike.com/site/EN/Models/Thys-222-Revolver/pnCurrent:3/</a>



### **Simplification for the UTRB**

One drawback of the particular way that the Thys design accomplishes this goal is by having the peddles and pulleys mounted on the same track. Although this seems to integrate two functions into a single element it also creates the need for the slider rail to be very tough so that it can withstand moments generated by uneven application of leg power. The precision required to construct the Thys rail would cause it to be too expensive for this design objective. This can be achieved by mounting the peddles to a bar that rolls along the top surface of the front support. The double pulley could then be mounted at a different location on a light-weight track that would only need to counter-act slight moments generated by the mass of the components themselves.

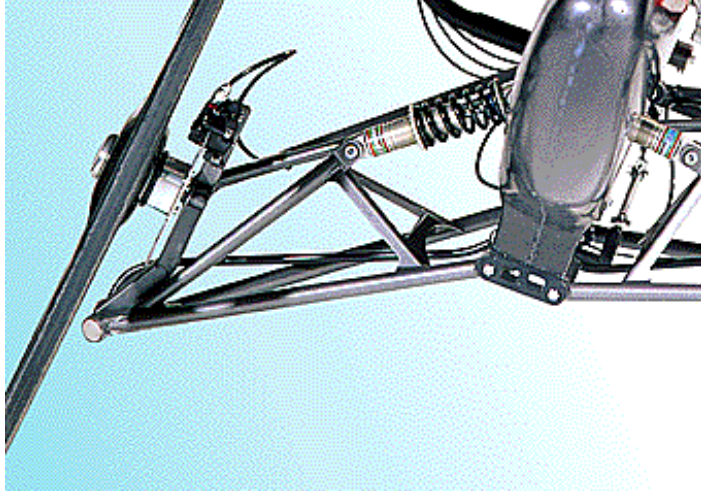
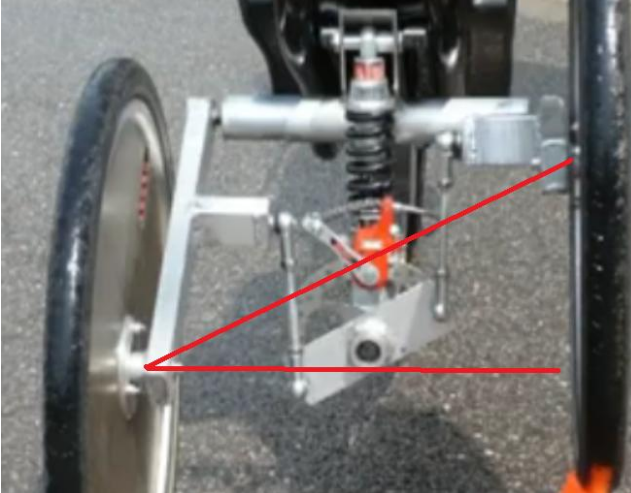
Instead of utilizing the complex Snek design, the UTRB will utilize a single speed and thereby reduce the cost of the mechanical elements of the drive train. These cost-savings are possible because of the powerful electric assist which will provide adequate acceleration for safe operation in the urban environment regardless of skill-level.

### **6.3.3 Tilting Method**

There are two primary ways to create a tilting three wheeler and they include. The first is a four-bar parallelogram linkage similar to that used in modern car suspensions but modified for tilting. The other design is the swing-arm linkage concept where tilting is achieved by the arms moving in opposite directions along a common pivot point.

The most important reason to select the swing-arm design is the very low parts count required to create a full-suspension version. The Munzo TT only has 7 linkage parts and a single shock absorber. The minimum complexity of a parallelogram is 7 with two suspension elements (as seen in the Tripendo below).

## Tilting Methods Table

Parallelogram Tilting	Swing-Arm Tilting
	
Image Source: <a href="http://www.tripendo.com/EDEFAULT.htm">http://www.tripendo.com/EDEFAULT.htm</a>	Image Source: <a href="http://www.fastfwd.nl/">http://www.fastfwd.nl/</a> + Own Work

### 6.3.4 Power Assist Sizing & Power Requirements

There are a number of drivers for the power assist specification. They are as follows:

- Maximum acceleration (comparable to 8 second 0-60 or  $11\text{ft/s}^2$ )
  - A 1hp (745 watt) motor is more than enough to accelerate a 50lb vehicle with a 250lb person at  $11\text{ft/s}^2$ .
- Maximum operating power
- Replacing human power during recovery stroke
- All-day use without recharging

#### Range: Battery Sizing

The average person living in Boston travels a maximum of 7 miles to and from work and an additional 26 miles at a maximum after work running errands, meeting friends and on other activities. This would suggest a maximum week-day trip distance of 40 miles. Weekend travel range requirements can be somewhat higher. If we assume an average weekend

activity time of 2 hr and an average tip length of 7 miles, plus an average of 12 active hours in a day then you arrive at  $(12/2)*7$  or 42 miles as the maximum weekend trip length.

These very rough estimates establish the maximum distance that a person using this vehicle would require at roughly 40 miles a day. This number can be roughly checked by comparing with the distance of a road bicycle race which start around 40 miles for the long race category. This check suggests that this range is roughly correct for the daily distance traveled by urban cyclists who use traditional bikes.

In order to use the vehicle for a full day of urban riding without needing to recharge the vehicle it is important to add the consistent drain on power that is caused by 'smoothing out the torque curve' with the power required in transit on an average day.

The total weight of the power assist unit will be 10lbs for the motor and an additional 10lb-20lbs for the battery pack. This yields a total added mass of 30lbs.

## **6.4 Conceptual Feasibility (*Claudio*)**

Prior to the detail design phase the overall parameters of the vehicle must be calculated.

These calculations form the basis for the overall functional scope of the project.

### **6.3.1 Drive-train Power Scope**

### **6.3.2 Tilting Geometry Scope (2)**

### **6.3.3 Form Factor Scope (3)**

### **6.3.4 Exercise Scope (*Claudio*)**

### **6.3.5 Safety Scope (4)**

### **6.3.6 Cost Scope (5)**

## **7 Subsystems, their properties and their sources (*Claudio*)**

### **7.1 Handel Bar, Peddles, Seat**

### **7.2 Slider and Support Assy.**

### **7.5 Drive-Train**

- The drive-train is the same as the thys rowing bike but with a simplified track system
- This design moves the drive wheel from the back (as in the Thjs art) to the front wheel (as in the Munzo TT)
- Dewalt motors<sup>14</sup> are light and powerful

## **8 Prototype Specification and Testing (*Claudio*)**

### **8.1 Most parts should be off the shelf**

- Use standard front wheel used for small bikes
- clip-less peddles will be used
- standard rear shock is used off of a different tool
- side mounted wheel hubs used for both rear wheels
- standard spokes are utilized
- standard track utilized for foot swagger track

### **8.2 Easy Assembly (in bike shop)**

- breaks into two sections (front and back) for storage and when stowed
- all usual fasteners utilized

### **8.3 Under 500 for raw materials + Sponsored materials**

- In order to rapidly create a prototype to use in the evaluation of the general concept, a prototype will be constructed using a combination of plywood and honeycomb cardboard core material. Frame, seat and rear swing-arms will be constructed from these materials. The final design will include different materials for added strength at much lower mass but the basic construction concepts should remain unchanged.

### **8.4 Testing performance**

## **9 Discussion**

### **9.1 What you accomplished to put together (*Claudio*)**

### **9.2 What you would have liked but could not find, make, afford**

- I would have liked to improve the locking mechanism on the Munzo TT tilting linkage so that the bike would remain upright at stops without the use of an on-off switch or lock. Several ideas have been developed in the course of this project to address this but none that were sufficiently simple to develop to be completed within the project timeline. One idea was to use a torsion spring and a long lever that acts to counteract the spring while the vehicle is in motion. This combination is perfect because such a long lever arm can be deployed as the post for a signaling tower used to alert drivers and make the vehicle's presence known. The following is a crude description of this solution. A driven tilt system with some linkage that allows the steering handle to also control tilt-angle would have been the best solution because it makes possible 'anticipatory tilting' that seems to make the Tripendo more sporty than other systems. It is not clear whether or not the above momentum-based tilting actuator would be able to induce a lean fast enough to allow for rapid turn actuation and provide for equal performance to a driven system.

- An additional idea that could make the signaling system better is to incorporate an "air brake" into the signal tower depicted above. This air brake would serve the dual role of providing greatly increased aerodynamic drag to assist in stopping while also drastically increasing the visibility of the vehicle to motorists. The internal surfaces of such an air break could be painted a bright shade of red and illuminated from the top to further signal motorists. This particular concept would be a very unique sight and would also add considerably to the tilting trike 'gene pool'.
- Another concept that would have been interesting to try but was too complex was to re-design the hydraulic components and pressure versatile used in the Apex *hydraulic*;leaning and shock absorption system. In it's present state, the Apex system uses existing hydraulic rams and off-the-shelf components. Very few hydraulic applications require small form-factor and light weight and for this reason the components have of room for improvement as part of a bike suspension. If this project had unlimited time and financing it would have been interesting to develop light hydraulic components.
- It would have been interesting to re-work the Black Max design below to incorporate a low-cost suspension linkage for each rear wheel. A power-assisted version that utilizes this linkage could incorporate one or two hub-motors to provide power while incorporating a sealed-track system to control the travel of each wheel. Such a system would be very stiff and allow for reduced material weight because there would be no need for long arms. Another advantage of this particular design is that it can be configured to provide 45 degree tilting angles without lowering the center of the vehicle.



Image Source: <http://www.fleettrikes.com/blackmax.htm> + Own Work

- Yet another design idea that I would have liked to be able to develop is a tilting delta trike with active control over tilt angle via some linkage. A fly-by-wire solution would be well suited for this task the bike is well balanced and does not require excessive force to control. Perhaps a more feasible approach is to attach two lines to the handle bar instead of just one. As the handle is pulled asymmetrically one a pulley mounted where they join would turn. This turning action could wind a separate cord that travels back to the rear linkage. Yet another idea is to have paddles mounted next to the seat such that tilting can be controlled by pushing back with elbows at the end of a stroke. In general, stokes would be made on flat ground or when exiting a turn and thus having the rider remain in the compact position while entering a sharp turn would not pose real limitations on power production. This final idea would preserve the simplicity ideals of the Munzo TT and this project.

### **9.3 Comments on future manufacture at scale**

In order to apply this design to the market and attain the desired cost profile there are a number of important steps that need to be completed. This step should be associated with a complete cost model and a vendor selection process. The cost savings with volume should come from material bulk price reductions and in improved assembly speeds but should not



come from optimization. These bikes should be built using 2D construction methods and should be made to order. The prototype should mirror the final design but with different materials and using more manual cutting and assembly steps. One key element in the preparation for the sale of this product is to complete a full set of drawings with appropriate tolerances. These drawings must be associated with computer simulations of structural strength in each frame member. Computer modeling will support a process of continued improvement of the structure and composition of the frame design such that the cost continues to fall over time. It is expected that new composite materials using fibers such as synthetic spider silk and carbon nanotubes will dramatically reduce the cost of high-strength composite materials and thereby make the above fabrication methods drastically more cost-effective than welded-metal alternatives. Up until this point the process of manufacturing carbon fiber composites has been constrained by the energy intensiveness of the fiber production processes to date. The advent of new materials that utilize low-energy biotic processing methods completely change the cost dynamics of creating high-strength fiber. Within 5-10 years fiber-reinforced fibers will be a cost-effective alternative to metals.

#### **9.4 Suggest next steps or improvements**

- Incorporation of an enclosure for better all-weather use and for increased top speed is one thing that would make this bike concept more useful in larger urban areas, rural areas and in cities that have more rain.
- Computer modeling and optimizing a single carbon-fiber frame can significantly reduce the weight of the bike and may not cost more to produce because of the reduced component count. It is imagined that the leg support, seat and all mounts and pivots be made in a single integrated piece. The other parts would be the fork, handlebar, leaning/suspension linkage and the main swing-arms.
- A full design for manufacturing is required in order to convert the designs developed in this report into a low-cost option for urban transport. An assessment of minimal production volume in order to achieve low cost is one element of this assessment.

## **10 Conclusion (*Claudio*)**

It is clear that rowing as a mode of human power is both a good means of transit and an excellent full-body workout. The strategy of simplifying the bike design as much as possible aided in meeting the cost-reduction goals of the project while having an added benefit of reducing weight. The use of the Thys rowing bike pulley system helps by replacing the chain with a simple cable that does not rub against any other elements. Because there is only static contact the tolerances can be much wider, further reducing cost in production. The most expensive system in this bike design is the power assist. At low-volume production the power assist accounts for a large cost and pushes the bike outside of the design specification but if produced in high volume it can be produced within the budget of \$1000. Battery and motor technologies are improving rapidly and their costs are falling at the same rate. Over time, this bike concept will become much more affordable and accessible to a wide range of urban people.

Urban-ism is the future of human civilization and the UTRB is one interesting addition to that landscape.

## **APPENDIX:**

### **A. Intermediate Wants Vs. Needs**

#### **I Design Goal**

The goal of this project is to produce a vehicle concept that will appeal to people living in cities who would like to incorporate more physical exercise into their daily schedule without having to commit extra time to do so. This class of individuals is made up primarily of young professionals, college students and generally health and environment aware individuals. One of the earliest decisions we faced in the design process was what the maximum speed of the vehicle should be. The decision to maintain a cost of less than a small car (\$12,000) is a condition that governs the top speed that the vehicle can attain. For this reason the project's specifications include a top speed more in-line with that of a cyclist rather than an automobile. Power assist technology is used to enhance acceleration and smooth out the power delivered at the wheel. The other major consideration is that the vehicle be designed so that it is safe while turning in any road condition. The overall goal of this project is to accommodate the needs of an urban traveler by providing an active alternative to public transit that uses new modes of power management.

#### **II Design Elements**

- Rowing
- Tilting
- Small windshield
- 2D construction methodology
- Minimize: Cost
- Minimize: Complexity
- Maximize: Smooth ride

### III Basic Requirements: Feature List

- A. Pick up groceries and run local errands. Commute to work and back. (effective)
- B. All-weather operability (effective)
- C. To provide an exciting riding experience that is comparable to that of a sports car or a motorcycle (fun)
- D. It must have a human-powered component so that the rider will gain exercise and a feeling of auto-locomotion. (fun) This provides the dual commute/workout experience. (convenient)
- E. Storable small form factor for off-street parking and easy shipping. (convenient)
- F. Comfortable with good air circulation, an ergonomic chair with healthy body positioning and a low ambient noise level. (effective)
- G. Low cost (effective)
- H. Safety: must both protect passenger from impacts while providing better situational awareness to avoid accidents (effective)
- I. Reliable, requiring low maintenance and delivering low risk of failure (convenient)
- J. Good range, comparable to an average car with heavy peddling. Maximize the impact of human power by reducing weight while still achieving a min range of 150 miles @ 55-65mph. (effective)
- K. Passenger is of a reasonable range of size and shape and only one adult person(convenient)
- L. All (non-freeway) roadway operability (effective)
- M. Easy to use (convenient)
- N. A means to achieve a good cardiovascular workout

### IV Weighted Table: Derived from (III)

<b>Value (1-5)</b>	<b>Parameter</b>	<b>source</b>	<b>Want Value</b>	<b>Need Value</b>
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			40mph in order to	
			maintain secondary	25mi/hr for safe urban
4	Max Speed	A, C	highway speeds	transport
			Enough for a long trip, 50	Same as twike, 20 miles @
			miles @ 40mph average	55mph average speed,
			speed w/ backup power	backup power supply for
5	Min Range	J	source for longer trips	longer trips
				small enough to fit in a
			small enough to fit in a	motorcycle parking space or
4	Parking	E	bicycle parking spot	smaller space.
			comfortable seat with	
			venting, quickly	
			understood controls,	comparable to a recumbent
4	ergonomics	F	comfortable neck angle	bicycle, "sporty"
			faring, roll bar plus, an	
			airbag system that	
			deploys when appropriate	
			biofeedback is received	
			from driver, 5 point	
4	Safety	H	harness.	wind shield, helmet
			Vehicle can be	
			somersaulted into or	
			pulled down and entered	
4	Entry/exit (novel)	N	from through the top	entry through the top
			Appealing enough to	
4	Overall Look	N	justify a 50k price tag	looks more like 15k
			Like a motorcycle in	Like a road bike in
3	fun to ride	C	performance	performance

3	Acceleration	C, A	0-60 5seconds	0-60 10second
3	Total Device Weight	E	100-150lbs	250-300lbs
			A misting device is included to wash away sweat so the rider can change in the parking lot or at a restaurant	Work locations must have showers
3	Sweat Consideration	F	turn, break, hazard, headlamps, a directional horn	
3	Signals	H	All cars can be seen though a combination of cameras and a large windshield area	turn, break, lamp, basic horn
3	Visibility	H	lasts 5 years without maintenance	A large windshield provides for good visibility
3	Corrosion resistance	I		repaint every 2 years
3	Fatigue life	I	500,000 miles equivalent	100,000 mile equivalent
	Passenger dimensions		120lbs and 5'3" to 220lbs and 6'4"	180lb and 6ft with a range of +/- 10lb and +/- 2in respectively
3	Modularity	K	Each component can be replaced in 10 min	some components take 6 hours to replace
			An attractive appearance, low cross sectional area and Cd	Comfortable and safe cornering at higher speeds
3	Faring Shape	N	Variable resistance to fit rider and workout type	Single resistance setting, or linked to speed
3	Exercise level	O, D		

			4 bags of groceries or a	
2	Storage	A	weekends trip supplies	One back pack
2	human power impact	D	50% range extension	30% range extension
			Bicycle classification so	
			that it can be operated	
			without a license (this	Can be classified as a
			requires that it not go over motorcycle and operated as	
2	Legal Classification	E, G	30mph under power only.) such.	
			Like that of a road bike,	like that of a moped, use an
2	Noise Level	F	nearly no noise	Ipod
			roomy interior with the	a small shell slightly bigger
			same spaces as the	than a two wheeled
2	Interior	F	carver	streamer
			under 3,000 or about	Under 15,000 which is about
			twice a good mountain	how much a new touring
2	Cost	G	bike	Yamaha motorcycle costs
			GPS, front and rear	
			cameras, body tension	
			sensors to activate safety	
			measures, radar, battery	
			level indicator, strain	rear view mirror, battery
2	Control equipment	H,C	gauge indicator on frame	level indicator
			Room for two with the	
			passenger straddling the	
			driver, adding 2 ft of	One person and cargo
2	Occupancy	K	length.	space
2	Ground clearance	L	4 in	2in

2	Roadway Conditions	L	Gravel, Snow and trail: OK	only paved roads that a sports car could ride
2	Battery chagrín	M	Detachable battery can be one permanent power interchanged and charged source	
2	Charging Time	M	6 minute charge with ultra capacitors	6 hour full charge
1	Weather	B	Hot, cold, heavy rain, high impact of heavy winds, no winds, some snow	hot, cold, medium rain, mild snow
1	Lateral Acceleration	C	nearly 1 gravitational constant (same as the carver)	Equal to the tripendo, 0.48 gravitational constants
1	Transport	E	Battery and wheels can be removed to be stored in a station wagon.	needs trailer
1	Maintenance	I	every 1 year	every 4 months
1	Battery cycle life	I	1000 (150,000 miles)	500 (50,000 miles)



## **B Project Scope Outline Report**

Zebediah Tracy, 09/29/09

Title: Project Scope and History

### **Documents Created Thus Far**

Phase One: (complete)

*Initial project objective statement* and rationalization created. The general goal was to create an interesting vehicle that would be useful as a means to commute to work and around town while getting a workout.

*Needs vs. wants table* was created in which all of the key variables related to the vehicle were turned into parameters and given a subjective value 1-5.

*State of the art* was conducted resulting in a spreadsheet of roughly 10 of the most interesting “edge cases” of personal, human-powered and leaning vehicles. This list included entries ranging from velomobiles to the 150 hp carver.

### **Phase Two:**

**A blog** was created to chronicle our progress as Claudio and I began to re-develop the project concept and work out our roles in the new team.

***Robust State of the art form*** was created in order to track the many new technologies that we were finding ranging from the RowingBike to the GreenWheel and others. (this form has proven overly complex and very difficult to use without it breaking).

Email correspondence with the ***designer of the CarCycle*** including feedback on various ideas including the concept of integrating a larger electric assist to discussing the trade-offs involved in going with a rowing design. This is a valuable contact given that the CarCycle is one of the most impressive velomobiles I have encountered after reviewing thousands.

Email correspondence with the designer of ***the Thys Rowingbike*** who had developed a new driveline and linkage specific to long-distance riding. The system may even be an improvement over traditional chains and cogs because it has far fewer moving parts and is lighter.

### **First Choice:**

- 1) **create a human vehicle that is practical and fun (5K price range)**
- 2) create a fast vehicle that uses some human power to extend the range and create a more fulfilling riding experience. (50K price range)

We are forced by sheer economics to stick with the former option because we intend to actually build something and it is far outside of our budget to construct a high-speed vehicle.

### **Summary of design objectives:**

The goal is to create a single occupancy vehicle with the following criteria;

1. Has a Thys Rowingbike power-train
2. **A secondary power source in the form of an electric motor and battery are included for short bursts of speed (GreenWheel)**
3. Has three wheels either two in the front or two in the back in order to give it more stability on wet, icy and loose tarane.

4. **A mechanism that allows the bike to “lean into turns”**

5. Target price: \$5,000

Stuff other people can worry about:

- Improving the electric drive train
- building a good enclosure
- incorporating a suspension linkage
- building a production spec and prototype
- Integration of a protective roll cage
- Vehicle will fold up so that it occupies less space on the sidewalk & can be entered from the back by flipping into the cockpit.



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