Design and Development of the Turanga Velomobile

Suhas Malghan
Turanga Product Development

Abstract

Velomobiles have not entered the mainstream of transportation in the US despite the fact that a velomobile would have great utility to a growing segment of society. This paper describes the design and prototype build process thus far to bring a velomobile designed for the American market and consumer. It's design features include a bamboo/balsa laminate structure surrounded by a lightweight fabric and Coroplast body as well as tilting capability, full suspension, nearly stepless gearing and front wheel drive. The prototype is mid-way through the build process as the chassis has been constructed with the body yet to come. Design, manufacturing and marketing issues pertinent to the US market are also discussed.

Introduction

In an age of high energy costs, roads filled to capacity and the underserving of communities by public transportation systems, there exists a need for a mode of personal transport that requires no petroleum and is suitable congested environments. Velomobiles, fully enclosed human powered vehicles, enable gas-free travel short distances in comfort regardless of the weather. Besides improving the physical fitness of the user, a velomobile saves the owner from the typical hassles of owning a car in the city such as parking, maintenance and insurance.

Company Overview

Turanga Product Development (TPD) was founded in January 2004 by Suhas Malghan as a design firm dedicated to developing sustainable transportation design solutions. Previous projects include the conversion of a 1989 Toyota MR2 to battery electric drive along with the ongoing development of a velomobile, a fully-enclosed, three-wheeled human powered vehicle that allows a rider with cargo to pedal around town in comfort regardless of the weather.

After evaluating the potential to apply sustainable product design processes to other products such as bicycles and motorcycles, the idea of developing a velomobile became the most attractive option due to its incredible potential to transform transportation in the US, a market ripe for growth and the lack of a product designed for the North American customer.

TPD is based in Baltimore, Maryland USA.

Outside of the enthusiast community, velomobiles are nearly unknown in the United States despite the fact that bicycle commuting is enjoying significant growth and many people would appreciate the advantages they would offer. The ability to cover longer distances protected from the wind and inclement weather while carrying cargo is immensely useful to many existing bicyclists while also addressing the concerns of people who don't yet use human powered transportation but are receptive to the idea.

The Turanga velomobile has been designed to appeal to both these groups by offering personal human powered transportation that combines the utility needed to displace short car trips while delivering a riding experience that appeals to seasoned bikers.

Customer Survey

Through many conversations where the idea of velomobiles was presented and discussed with all types of people, it seemed that the responses could be categorized into 3 camps.

- Type A - Hardcore current bikers who already use a bicycle for most of their daily needs year round or nearly so. Take pride in the fact that they bike and are very interested in furthering bikers' rights. Not as enthusiastic about velomobiles as one would think as they are happy with the current state of the art but nevertheless curious. Velomobiles are seen as complicated and unusual. They like light and simple machines and don't want to bother with motor assists and other heavy components.

- Type B - like biking and would like to do more, would do more if circumstances (location, commute distance, traffic conditions, climate, etc.) were more favorable. They're very much intrigued by the idea and often ask about motor assist and integrated child seats (or at least an attachment point for a child trailer). Given, the price premium over a conventional bike, they'd like the velomobile to be versatile enough to be used in may different scenarios.

- Type C - People who don't bike regularly but make nearly all their short trips by car. A velomobile could substitute for the car but the idea meets with great resistance, primarily because the concept of not using a car to get around is so unfamiliar. They may be curious about the idea but believe it is more appropriate for other people.

Operating Environment

Human powered vehicles as a legitimate means of transport are gaining more traction in the US but it is still seen as an accommodation to a special interest group. Roads are still seen as primarily for cars and with a lack of separated bicycle infrastructure, riders are forced to coexist with cars in the same space.

Nevertheless, bicycle use is increasing and city planning is now incorporating bicyclists and pedestrians into the road use mix.

Mixing bicycle and auto traffic requires extra vigilance by both parties and it's very much in the bicyclists' interest to be as visible as possible. Visibility is of special concern as velomobiles are much shorter than typical bicycles and are more difficult for drivers to see when riding alongside. It is especially disconcerting for velo riders' sightline to be at vehicle bumper height. A velomobile will have to find some way to retain the aerodynamic advantages of low height while still being visible to surrounding cars and trucks. Front and rear lights, retroreflective clothing and hand signals help increase bicyclists' visibility and road presence while strong brakes, high maneuverability and a comfortable ride allow the rider to pay attention to the vehicles in the vicinity, confident in the abilities of the machine to handle any situation.

Urban roads in the US are generally rough and pockmarked with pavement irregularities, manholes covers and pebbles and glass at the edges. Riding a bicycle requires attention to the road surface to prevent damage to the bike/rider and possible loss of balance and control.

Velomobiles address these concerns with the stability of three or even four wheels and puncture resistant tires. Yet not all velos possess the ground clearance, approach angles and suspension to handle the speed bumps and short curbs that dot the US landscape. This new design would have to take this terrain into account so that potholes and bumps would be absorbed by the machine instead of the rider.

Weather is also a large variable in the US with nearly every type of climate represented. At our Mid-Atlantic region home base in Baltimore, Maryland USA, all four seasons are strongly represented with cold winters (with a few snowfalls every year), rainy springs, hot and humid summers and chilly autumns. Rain is possible all year round and weather prediction is not very accurate such that it is not uncommon to be caught out in an unexpected rain shower. Daylight hours also swing from 15 hours in the summer to 10 hours in the winter.

A velomobile that could accommodate all these situations would need to provide rain protection, traction to power up inclines through surfaces from gravel trails to snow and enough ventilation that riding is still possible on hot and humid days.

The expense of a velomobile induces a great deal of anxiety in owner's since bikes are so easily stolen. There is nothing like a theft proof bike but it would help if the velo could be secured with a U-lock so theft is at least difficult. Another strategy is to make the velo easy to store in a secure area such as the entrance hall of a building or a secure yard space. A velo would need to have sturdy loops to attach a U-Lock and grab handles for the owner to maneuver the velo into a convenient place. Now what if the velo could be stood on end against a wall or hoisted up to the ceiling with a block and tackle?

Customer Functionality Wants

The velomobile section of the Turanga webpage included a short survey to help understand what prospective customers needs, wants and expectations for this unfamiliar vehicle might be. This was supplemented by many conversations with Type A and B customers as they contemplated how using a velomobile would fit into their daily routine. These conversations were especially helpful as it guided product development to more closely match customer desires, as opposed to copying existing products. The most commonly requested traits included:

- Tight turning radius for maneuverability
- Ability to fit through 30" (762mm) wide doorways
- Weather protection
- Reasonable price ($2000-$4000)
- Cargo room

Just as importantly, comfort features like heated grips were of little to no interest while electric motor assistance met with a mixed reception. Some comments were that they don't want to pay the cost and weight penalty of a battery-electric system and others were not familiar with how an assist system would work.

Common Barriers to Typical Bikes

These conversations were also illuminating as they pointed out aspects of current bike design that the typical consumer finds frustrating. Most of these points centered on drivetrain issues.

Derailleurs and the requisite chain were criticized for the potential for the chain to soil pants legs and the front sprocket to rip cuffs. These points could be addressed with a chain guard yet hardly any bikes today come with one. The multiple speeds offered by derailleurs are welcome but sifting through a wide range of gears trying to be mindful of the proper front and rear sprocket combinations is a tedious affair as well as the inability to shift at a stop. Both of these aspects become more critical when the additional weight and higher speed potential of a velo are factored in. It's much easier to be caught in the wrong gear after a quick stop and then not be able to accelerate with the flow of traffic

Turanga Velomobile Design Process

"Sustainable transportation design" is Turanga's motto and to satisfy that mission the velomobile was designed to make a distinctive statement about sustainability.

The word Turanga has two meanings: in Sanskit it means "horse" and in the Maori language means "place where you stand." The synthesis of these two definitions is the idea behind vehicles that work as well moving as they do standing still. The joy of movement should be complemented by the products' harmony with its environment while stationary. This includes its inevitable disposal.

Along with its environmental compatibility, a Turanga velomobile must share the company ethos of being fun and sporting to ride as well as being functionally and aesthetically refined yet adventurous.

The vehicle architecture developed over several months and was informed by benchmarking a Catrike Speed. The Speed had a very high quality feel but its limitations when used as a commuter quickly became apparent. The 33º seat angle felt too reclined and forced the neck to bend excessively to see forward. The vehicle was also too low as the main spar scraped the pavement when going over speed bumps and riding on the street was intimidating with such a low riding position. The ride was also punishing over bumps as it's naturally harder to avoid bumps when the vehicle has three tracks to hit a bump, as opposed to one of a bicycle.

Turning showed the most vivid limitations of the vehicle and nearly all other trikes; the high speed potential (and the Speed in particular is quite fast) is tempered by the ease of overturning the trike in a turn. The bicycle wheels used in trikes are not designed for lateral forces and resulting deflection due to cornering forces is unsettling as well as resulting in disc brake contact, slowing down the trike. Preventing overturning requires vigorous body positioning that significantly increases rider exertion.

The other dynamic shortcoming discovered was braking stability. Modern disc brakes are very powerful, powerful enough to easily cause "endo-ing" during sudden applications. Unlike a bicycle, it's harder for a trike rider to shift their bodyweight to affect the vehicle dynamics. It was quite easy to lift the rear wheel under braking and there was little the rider could do to prevent that.

This information shaped the chassis design. The customer research, along with the shortcomings described here and shared by most every trike, offered a great opportunity to advance the state of the art. Listed below are several of the key design features along with more in-depth description of the structural design, drivetrain and suspension/steering systems.

Design Features

- Tadpole layout with tilting capability and rear-wheel steering
- Bamboo plywood/balsa sandwich structure for inexpensive manufacturing and easy assembly with future design modifications possible
- Narrow 29" allows passage through doorways and fit in bike lockers
- NuVinci CVT and Schlumpf MountainDrive provide wide, nearly stepless gearing range while being able to shift at a standstill
- Full suspension
- Front and rear grab handles, front handle doubles as "anti-endo" bar
- Full lighting with rear view mirrors and retroreflective visibility markings.
- Enclosed chain runs
- Storage compartment
- Nonstructural, breathable waterproof fabric body with Coroplast structure and full transparent plastic canopy

Structural Design

To meet the overall product goals, the structure needed to be accurate, light, sustainable, inexpensive to manufacture and adaptable to new models and configurations,

The typical welded tubeframe HPV structure is a labor intensive item involving tube bending, notching, fixturing, prep, welding, grinding and finishing. Jigs and tooling are required and the process is mostly manual, hence costly and slow. A better answer was sought.

Many HPVs utilize a monocoque composite structure to reduce weight and part count. This is an attractive option for low volume manufacture but composites are labor intensive, slow and require significant tooling investment. A new configuration of a product, such as adding a new size or seating configuration, would require more tooling investment and take up storage room when not being used. There is also the issue of the large amount of waste inherent in composites manufacturing as well as chemical exposure issues.

Structurally, it is arguable that a monocoque is an efficient structure for this application as there are distinct heavy point loads on the structure as well as areas that handle very little load. Rider weight and pedaling load are quite substantial compared to the relatively paltry aerodynamic loads the bodyshell sees. Unless material thicknesses can be closely tailored to the load profile it is likely to result in a heavier structure than necessary.

The decision process finally wended down to utilizing a main structural spar to absorb the high static and dynamic loads enveloped by a lightweight body. This modularity would allow variations and revisions to be made to one component without affecting the other and concentrate the right material in the correct amounts to the right places.

Organic materials were investigated for their sustainability and aesthetic appeal, especially the bamboo laminates that have a reputation as tough and durable. They also bring an invigorating natural aesthetic to the vehicle that sets it apart from anything on the street. The idea of waterjetting a sandwich laminate was developed as it could result in a quickly and accurately manufactured structure that could be revised without any tooling costs penalty.

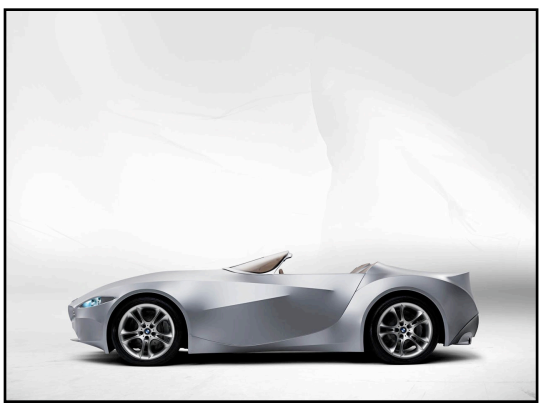
The resulting structure is a boomerang shaped sandwich structure consisting of 1/4” multidirectional bamboo plywood skins on either side of a 1.75” thick balsa

core. The lamination is performed at the balsa supplier’s facility in a hot press and then mounted in a CNC router that cut six spars from an 8’ x 4’ laminate and drilled all the holes for component attachment. The prototype units came out very flat and true but the mechanical routing leaves a ragged edge on the balsa. Waterjetting would leave a cleaner edge but for now the laminate is sealed with two coats of shellac.

The prototype run of spars was also made incorrectly by the supplier, utilizing 1.25" thick balsa but was corrected with extra bamboo laminate. The resulting structure is overbuilt and heavy but more attractive with the contrasting honey-colored panels.

The seat is a similar structure utilizing unidirectional bamboo veneers on either side of a .25" thick balsa core. This piece was vacuum bagged with room temperature cure marine epoxy bonding the laminae together. A higher production technique will be developed in the future but this method was adequate for prototype purposes. It was later manually trimmed to profile with a router. A variety of padding materials are being experimented with, including cork.

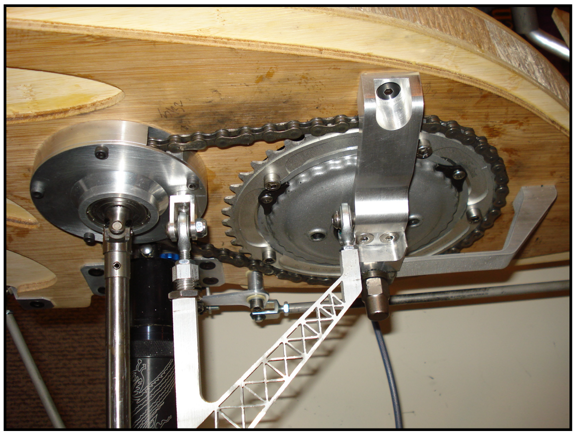
The shell is still in the design stages but the concept of utilizing a waterproof, breathable fabric and Coroplast appears feasible. The inspiration for the use of fabric actually came from the automotive world through the BMW GiNA concept that showed how lively and resolved the body surfacing could be made. The idea of using a fabric cover had been considered and discarded previously as it was not seen as capable of producing an attractive form but the GiNA concept shows the great potential inherent in the material.



Drivetrain

The drivetrain went through many iterations in the CAD program, initally starting with a conventional rear drive layout. The conceptual idea was to utiliize an electronic CVT as proposed by Andreas Fuchs which would provide a clean, shiftless and very flexible drive system that could easily be supplemented with electric motor assist in the fture. Unfortunately, no such system was readily available and after consultations with companies that could develop such a system, it became obvious that development would be far too expensive a project at this time.

A nearly equivalent mechanical system was developed using a NuVinci CVT and



a Schlumpf MountainDrive. Combining these two systems resulted in a wide, nearly stepless gear range that could be shifted at a standstill and was very straightforward to use as there were no permissible chainring combinations that had to be memorized. Neither component is light nor inexpensive though. Chain runs are relatively short and simple; from the Schlumpf to NuVinci to a differential and then out to articulated driveshafts connected to the front wheels. The Schlumpf can be moved fore and aft to adjust to different riders while a spring loaded chain tensioner takes up the slack.

Suspension/Steering

In order to satisfy the disparate requirements such as narrow track and tight turning radius while still leaving room for the rider, the resulting design became a front drive, rear steering, tilting vehicle with air spring/shock units at each wheel.

Given the overturning potential of a trike through studying the benchmark example, a requirement to fit through doors would result in an even narrower track and only exaggerate this tendency. *Also,* though riding a typical trike is fun, it loses the joyful feeling of tilting into turns like on a bicycle. It was decided that if the track was to be narrowed then the velo must be able to tilt into turns. This would make the narrow width achievable as well as enhance the riding experience.

The rider controls the tilting capability with up and down movement of the control lever. The motion moves a linkage that moves the mounting point of the front shock units, hence leaning the velo. The linkage design, track change during tlit and spring preload keep the velo upright in absence of any control input.

Steering the rear wheel is done by moving the levers left and right which are connected to control rods that rotate the rear swingarm. The steering axis is

inclined so that deviations from straight ahead raise the velo, hence a bias toward straight line stability. Maximum tilt angle is approximately 15 degrees, limited by the maximum deflection limit of the driveshaft u-joints.

Future Developments

Even as the first prototype is built the second iteration is already in mind. Often it takes seeing something in the flesh, as opposed to simply the CAD screen, to envision a better way. Several areas that are certain to be developed further are the drivetrain and tilting system/suspension along with part and weight reduction.

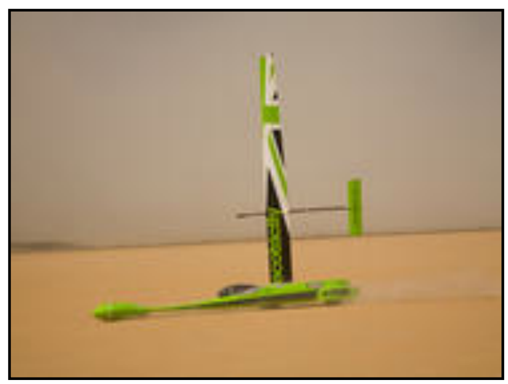
ATC Corporation, the makers of the NuVinci CVT, already offer a microprocessor and actuator kit that can adjust the CVT ratio in response to control inputs. There is great potential in developing this system to deliver the benefits of an electronic transmission at much lower cost. Currently the actuator hardware needs to be miniaturized to aid packaging but hopefully the next version of the system, along with a lighter CVT unit, is forthcoming.

Another advance that was not available during the first prototype build is a belt drive version of the Schlumpf unit. A belt drive would eliminate the mess of chain maintenance as well as save weight and produce less noise.

The suspension design will definitely be revised to incorporate more ball joints to replace the plastic bushing currently employed. This will reduce costs as well as speed assembly. The suspension arms will also be redesigned to make alignment adjustments easier and decrease waterjet time. The rear swingarm will be revised to simplify the spring mount structure. In the midst of these greater changes, the whole design will be reviewed to reduce weight (especially in the structure), refine aesthetics and increase functionality.

A common thread through all these efforts is the need to reduce costs and/or increase value. It remains to be seen whether an initial cost target of $2000-$4000 can be met but it will be pursued with great dedication. A significant fraction of the cost comes from the OEM components used like the NuVinci, Schlumpf and Cane Creek shocks so closer partnership with suppliers to achieve cost savings may be engaged in the future.

Aerodynamic development may also be necessary to ensure stability in cross-wind situations. An interesting avenue of development may be to explore the "apparent wind" effect employed by Richard Jenkins' Greenbird to recently break the land speed record for wind-powered vehicle at 126.1mph, more than 3 times wind speed.



Manufacturing

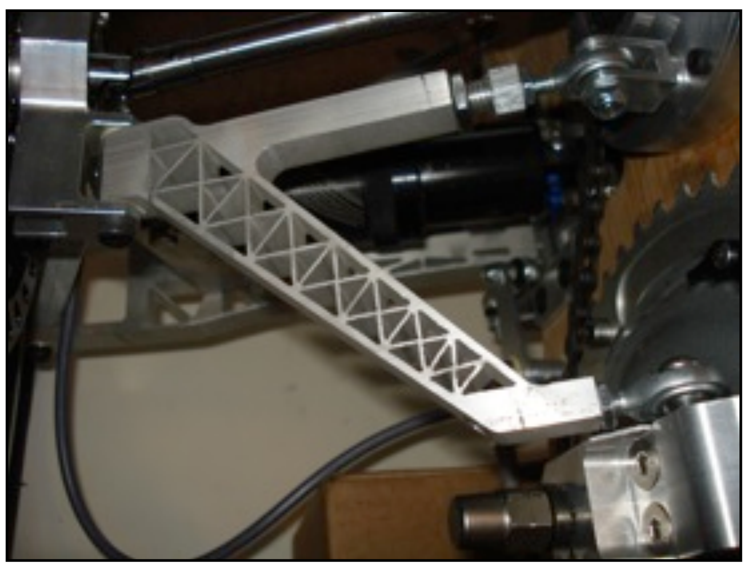
The current state of the velomobile field is of a cottage industry filled with a multitude of manufacturers offering distinctive designs produced in low quantities and with significant lead times. A comparison can be made to the early 1900's and the infancy of the automobile. As of this writing, the tenets of mass production have not been applied to velomobiles and most are produced using labor intensive methods. This is entirely appropriate to the current sales volume. There are some notable exceptions like the Aerorider and the Flevobike Versatile that make use of polypropylene composites for the structure. Thermoformable composites, as well as being recyclable, are much more suitable to mass production though the tooling costs remain high.

The manufacturing goals set for the Turanga velomobile were:

- Scalable manufacturing costs - Capital and tooling costs should be minimized so that low volume production can be made economical with little to increase in tooling costs as production increases. The number of manufacturing processes, machines, jigs, fixtures and tooling should be minimized.
- Use of environmentally friendly materials - Materials should be fully recyclable and not present any hazard to end user or manufacturing personnel.
- Effective use of material - Minimize cost by minimizing scrap. This means making the most use of stock material sizes.
- Express truth in design through the materials
- Reduce the number of parts

These goals were accomplished in several ways.

Manufacturing methods were consolidated to use as few machines as possible. A majority of the parts were made using waterjet cutting technology. This allows parts to be made quickly from flat stock with minimal time on the mill to cut bearing bores, if needed. In the next iteration, milling time will be reduced even further as bushings are replaced with ball joints. Suspension arms and certain drivetrain components lend themselves to this practice. In addition, components were made symmetrical such that front suspension arms can be used on either side.



Waterjet machining does have its limitations in that a vast majority of machines are only 3-axis, necessitating 2D designs with all operations done in only one plane and one setup.   This lends the velo a distinctive style with small cutouts carved out of flat stock. Visually it's a bit busy but also intriguing and certainly distinctive.

Marketing

The advantages to velomobiles are readily apparent to the growing constituency of people who are concerned about the health of themselves and the planet and are receptive to taking personal action to improve both. To that particular customer, convincing them to buy a velomobile may be as straightforward as building awareness and providing a suitable product at a fair price - a very left-brained proposition built on a logical cost-benefit foundation.

The vast majority of consumers - the type that the velomobile industry must court in order for the industry to grow - have to be convinced that a vehicle more expensive than comparable scooters or bikes yet powered by their own exertion is in their personal interest to purchase. To many customers, the idea of buying a vehicle is specifically to avoid the effort of moving under one's own power. How can a vehicle that requires work to move compete with that. A definitive answer is well beyond the scope of this paper but an appeal to the independent spirit and fun of velomobiling lays the foundation that a velomobile can deliver an experience and emotion that no powered vehicle can match.

Conclusion

TPD is very excited at the potential for a velomobile designed for the US customer and believes development so far is on the right track. Much work remains to be done but a steady level of investment will eventually result in series manufacture.

References

Fuchs Andreas. Chainless Electrical Human-Power Transmissions and their likely Applications. Proceedings of the 1999 Velomobile Seminar. Future Bike Switzerland, 1999