Backyard Roller Coaster Research and Development

Volume I: "Negative G" Out-N-Back Coaster

By Paul Gregg

Backyard Roller Coaster Research and Development

Volume I: "Negative G" Out-N-Back
Backyard Roller Coaster

By Paul Gregg
Chief Engineer

Edited by Kyle Gregg

July 2016

Dedication: To Belize, Rio, Mayan, Cruz, Westin, and Kensington. Nana would have never let me do this without you.

Copyright Information

Published by Backyard Roller Coaster Research, LLC
Provo, UT
www.backyardrollercoasters.org

First Edition Advance Copy 2016

All photos and illustrations by the author unless otherwise noted.

This book is in its first edition and we're looking forward to any reader feedback or suggestions as to how we can make it even better. The author is active on his blog on backyardrollercoasters.org, the backyardcoasters subreddit and is contactable via email at paul@backyardrollercoasters.org

Publisher's Warning- Before you read this book

Building a backyard roller coaster has inherent dangers, both in fabrication and use. Using hand and power tools improperly or ignoring safety practices while using a backyard roller coaster can lead to injury or even death. The operation of a backyard roller coaster has just as many safety risks. This book is not intended as an instructional manual. Do not use it as one. Our hope for this book is that by the numerous tests, certification, safety features and warnings contained herein that what is an inherently dangerous activity will be made safer by than it otherwise would be. The use or misuse of the information in this book constitute no guarantees or warranties of safety whatsoever. Your use of any information or materials in this book or on the associated websites is entirely at your own risk, for which we shall not be liable. There may be mistakes within this book. The information contained herein is intended to be of general interest to you and is provided "as is", and it does not address the circumstances of any particular individual or entity. Nothing herein constitutes professional advice, nor does it constitute a comprehensive or complete statement of the issues discussed thereto. Therefore, the text should only be used as a general and introductory guide and not as the sole source for backyard roller coaster engineering. While we have proscribed what we feel are adequate safety precautions for operating a small backyard roller coaster with total energy under 1000 Joules, we cannot guarantee fabrication quality, certification, or the safe operation of any backyard roller coaster. Backyard Roller Coaster Research, LLC or any other persons who have been involved in working on this publication, cannot accept responsibility for any injuries, loss, or damage that may result in the use or misuse of any of the information contained herein, nor be liable for legal prosecutions or proceedings that may arise as a result of it's reading or application. By reading this book you, the reader, contract with Backyard Roller Coaster Research, LLC to abide by this waiver. If you are unwilling to assume full and complete responsibility for your own safety and the safety of others that may result from the use of information in this book, stop reading now. If you do build a backyard roller coaster, by using it yourself, or allowing others to use it, you assume any and all liability for injury, death or harm that may occur. We advise that you give the same warnings to anyone who you choose to allow to use it, or even be near it when it is capable of operation. If any lawsuit does come forth it will be brought forth in Utah County.

Table of Contents

1.0 Introduction

So just why would someone want to design and build a roller coaster in their backyard? I've asked myself this question, a few times. I mean, it's all well and good to think it will be a real grandchild thriller, and even adults get a pretty big grin on their faces when they think about the possibilities. But there comes a moment when you stop thinking, go to the hardware store to purchase materials, and actually start building it. You find yourself in a checkout lane, with 14 PVC pipes and a load of 2X4's, exchanging glances with contractors and fixer-uppers, unconsciously keeping a watchful eye out for men in white coats, and think to yourself "If you people only knew what I was about to do!"

"It's a dangerous business, Frodo, going out your door. You step onto the road, and if you don't keep your feet, there's no knowing where you might be swept off to."
— J.R.R. Tolkien

Throughout history, invention and progress seem to have required a little bit of what I would kindly call "mental disengagement" at critical junctures. When you consider the engineering and architectural advances of humankind, many might not have happened without a touch of mental instability. I mean, look at the pyramids, airplanes, The Great Wall, the space programs, and others. I'm not sure they would have happened without someone who could, consciously or not, ignore resource limitations, pressing realities and consequences. Maybe that's why so many technical advances have occurred as a result of defense research (airplanes, jets, ships, computers, steel, aluminum, composites, microchips, etc.), which is a little sad. It would be nicer to just research things for peaceful purposes right from the start. Whatever the motivation, maybe it's OK, not always but just once in awhile, to ignore obvious questions, like "What am I going to do with a roller coaster in my backyard?" in order to make a very small bit of history, and to have some fun with your grandchildren.

"What lured him on was, of course, the great adventure, the eternal longing of every truly creative man to push on into unexplored country, to discover something entirely new---if only about himself. In that lies the detonating spark, the secret source of strength, which enables men to achieve the extraordinary." Heinrich Harrer

I retired from a large aerospace company in February of 2014, after a mostly interesting career, spent primarily in the research and development of new materials, joining processes, and structural architectures associated with aerospace vehicles. I had worked on many space, military, and commercial aerospace programs, developing and using a systematic approach involving the integrated disciplines of design, analysis, fabrication and testing.

It usually starts with a problem or a goal. Something needs to be lighter, or cost less, or there is a specific function which needs to be performed with high reliability. The better you define the problem, the better the whole process will be, so it's important to document your design requirements and objectives right at the start. The process usually starts (or should) with the designer, who interfaces with an analyst, or the analysis side of his own brain. It is a good idea to consult a lot of other people, as this is the time for looking at all possible solutions, a time of expansion of ideas and concepts. It's also important to include simple designs, as well as the latest technologies. I could tell you many stories from my career where a complex, expensive design was chosen, and we found out later something much simpler and cheaper would have worked.

At the University of Utah, where I went to college, the engineering department held an annual contest. One year, the task was to catch a raw egg dropped from a nine story building. Students came up with all sorts of complicated solutions, with whirling arms, layers of messy goop, hundreds of springs and such, but the guy who won submitted a simple large wash tub filled with sawdust. And it worked, really well.

A great designer is the type of person who, given a set of design requirements which include geometric volume available, loading, temperature, etc., can come up with ten or so brilliant design solutions within a few hours. Good designers have exposure to a lot of different kinds of projects and applications. I was lucky to work in a "central" research and development group, where you would work with a commercial airplane structure for a few months, and then switch to a new concept for something exotic, like a space station, then on to some futuristic military program. We were the technology "honeybees" of the company, building a large experience base, and skipping around to very different programs with innovative ideas. On a space or military program, weight was very important, no matter the cost, so the designs could be exotic. Whereas on a commercial jetliner program, cost mattered more, so we would define research projects which tried to keep the low weight of the space program, but lower the cost. I even had some exposure to boat and automobile structures, for some of the really low cost aerospace structures. Exposure to a wide variety of industries, projects and programs is a key to having a lot of design solutions rolling around in your head. Most importantly, you have to have a natural high level of curiosity about how and why things work.

"I have no special talent. I am only passionately curious." Albert Einstein

The next step after expanding the design concepts, is to narrow the ideas via weight and cost trade studies using analysis. This will turn out better if you try to quantify the trade criteria as much as possible. Weight, performance and cost are quantifiable, whereas appearance is subjective, beauty contests notwithstanding. Depending on how much time and money are available, you then narrow the concepts to a few of the most promising, identify the critical issues of each, do more in-depth studies, and then choose a primary concept. Partly to get manufacturing in the game

early, and partly to address the most critical issues, you then start to design element, subcomponent, or component tests configurations which will shed light on critical issues. The advantage of testing what you build, is that you get to know if your fabrication methods are any good, and the analyst gets to find out how accurate his or her methods are early on. The test results are fed back to the analyst and designer, and the process iterates until you have a really good design, along with calibrated analysis methods, reliable manufacturing processes, and a solid certification plan.

"Why do we have to grow up?" Walt Disney

Like many people, I've had a lifelong interest in roller coasters. As a young boy, I was equally fascinated and terrified by them. Well, maybe not equally. I found some backyard roller coasters online, a few pretty well done. But I thought I could make a few improvements in design, analysis, and fabrication methods. I also felt I could add to the safety aspects, and employ the more rigorous engineering certification testing methodology similar to what I had learned in the aerospace industry.

It is very important to have lots of people review your work. I had my engineer friends over for design reviews from time to time. You never know what you will learn when you get the view from another person's perspective. Sometimes it's hard to hear criticism, but you can always defend your point, while keeping an open mind to other ideas. I think some companies today may have lost appreciation for a good argument.

"Disagreement is the beginning of thought." Eric Hoffer

When you see engineers respectfully arguing with each other, progress is being made, problems are being uncovered and solved. Not long before I retired, I participated in a project where the manager didn't allow dissent. We were asked to review the project, and when we pointed out what we thought were a few flaws in the design, we weren't invited back. The program perceived technical reviews as potential schedule and budget killers, so they simply quit having them. Later, the whole program was delayed months when they had to fix the problems, at a very high cost.

One purpose in documenting my efforts is to tell my experiences with real world math, with the objective of providing encouragement to young people who might find themselves struggling with "math anxiety." When I was in middle school, I didn't really like math. I had an algebra teacher who taught math as if it was a foreign language of a country you would never visit. The emphasis was on whether you could remember the name of the algebraic principle you were using, with nothing about what you could do with it. Things improved in high school, with math story problem. Story problems were like fascinating little puzzles to me, a way to achieve seemingly impossible answers to questions, with no teacher opinion to assuage, as in politics and social studies. But it wasn't until I took freshman calculus in college that I really began to really appreciate the power of mathematics. My algebra skills were minimal, because I didn't understand algebra is really just a set of tools for solving problems cleverly. It's like teaching someone all about mechanics tools and never letting them work on a car. But calculus was very interesting to me, the idea that you can figure out things relative to time, that you can optimize things by setting a derivative to zero, and integration could find the area under a complex curve. But I had a hard time remembering how to use algebra to reduce the answers at the end of the problem, so I basically re-learned algebra by myself, this time with interest.

I can't be responsible for the design, fabrications, and safe operation of other people's backyard roller coasters. Most I see online look dangerous. This book is presented as a documentation of my "research and development" efforts regarding BYRCs over the course of a year. In the design, certification and governing safety rules, I have endeavored to make this experience a safe and enjoyable one for my grandchildren and myself. I have implemented a qualification process which I believe, in concert with rigidly following all safety rules and precautions, will result in a fun and safe experience.

When we embarked on writing this book, we wanted to speak to a variety of people, including young and old roller coaster enthusiasts, but also science and math students. Please don't be discouraged if you may not understand everything presented right away. Even if you don't understand something now, being exposed to new concepts is the first step to understanding.

We will discuss two types of backyard roller coasters. A roller coaster that simply goes out and back, making no left or right turns, is what I call a 2D (two dimensional) coaster. As of the spring of 2016, I have designed and built one 2D track and cart, two 3D (three dimensional) tracks, and three 3D carts, all unique designs. A 2D track and especially a 2D cart are much simpler to design and build. A 3D track and cart are more difficult, as the cart has to adapt to the track in another dimension. I will describe primarily my 2D efforts in this first volume, as it will be easier to introduce physical principles and construction methods.

✂•••••••••••••••••••

3.0 Safety

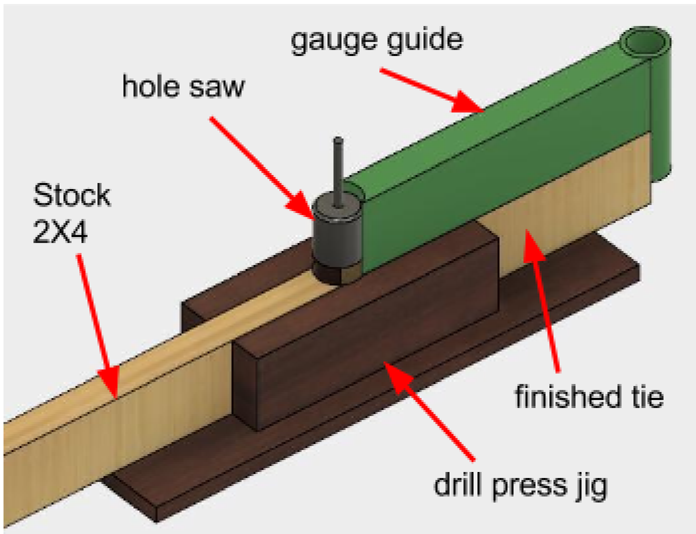
I wanted to build a fun roller coaster, with little risk to safety. The cart and track have to be able to survive repeated use, with some margin built in, but more important are the safety rules we adhere to with discipline. I came up with the following list of safety guidelines:

1. Use chain and padlock to prevent unauthorized use, or always store cart away from track.
2. No one but the rider and a supervising adult should be on or near the roller coaster when in use.
3. Use automobile grade lap safety belt on cart, attached through steel cart frame.
4. Cart design shall include provision which will under no circumstances let riders feet or hands get near the wheels and track.
5. Parental oversight is required at all times.
6. Surround coaster track with a fence or at minimum, caution tape, far enough away to keep other children out of arm’s reach.
7. No motorized lift hill, for safety, and to better ensure there is always adult supervision.
8. Lift hill will have anti-rollback provisions to prohibit the cart from sliding down backwards, in case the adult slips.
9. Certification of the roller coaster track and cart will be accomplished by dynamically testing with sandbags strapped to the cart. Sandbag weight shall exceed 1.5 times the maximum allowed rider weight. Certification testing will be repeated after any track or cart modifications, and at least every two months of operation.

✂•••••••••••••••••••

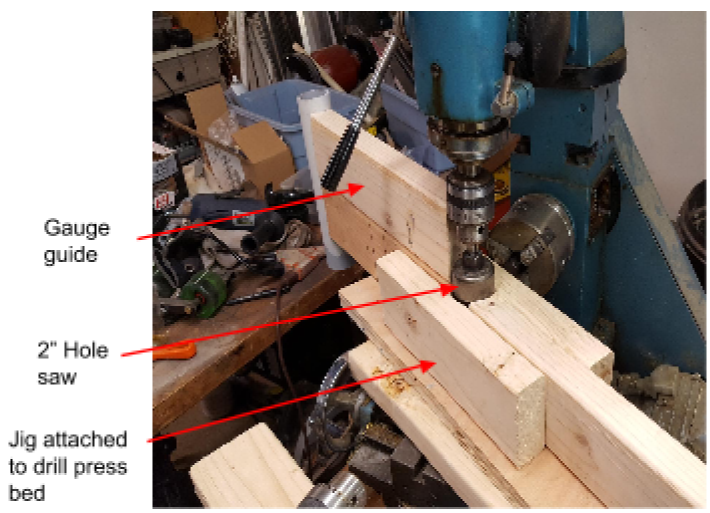
5.3.2 Track Tie Fabrication

I cupped the ends of the ties by setting it in a drill press jig, and cutting the ends with a 2-inch hole saw, two ends at at time (the outer diameter of 1-½ PVC is 1.9 inches, but 2-inches is close enough.)



The hole is offset to one side by 0.10", so the cart main wheels will have more clearance to the tie on the top side. I had to stop every inch of depth to clean out the hole with a chisel so I could go deeper. This might be avoided with a Forstner bit, an auger bit, or a deeper hole saw. I drew a "T" on the top side so I wouldn't install them upside down later when assembling the track. The most important thing is to make the ties with a consistent length end-to-end, as this will set the track gauge (distance between rails).

If the track gauge is inconsistent, or doesn't match with the wheel gauge, the cart will bind or be too loose on the rails.



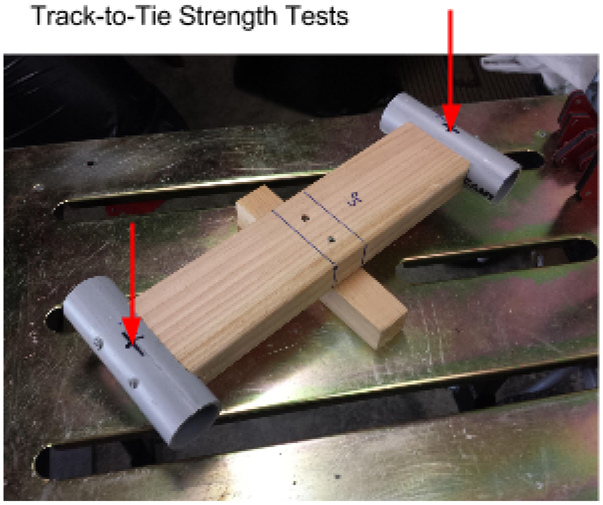
I accomplished this with a gauge guide made from a short piece of track attached to a "master" tie. I tried to make my track gauge tolerance within 0.1875 inches total. I set the jig up on my drill press, and made all the ties without detaching the jig, to achieve as much consistency as possible. I tried to avoid knots in the wood near tie ends. I started out making the cupped tie ends by using a diagonal guide fence, dragging the ends of the tie diagonally across my table saw blade about four times, taking a little off at a time. This worked OK, but it was dangerous and not as accurate.

✂••••••••••••••••••••

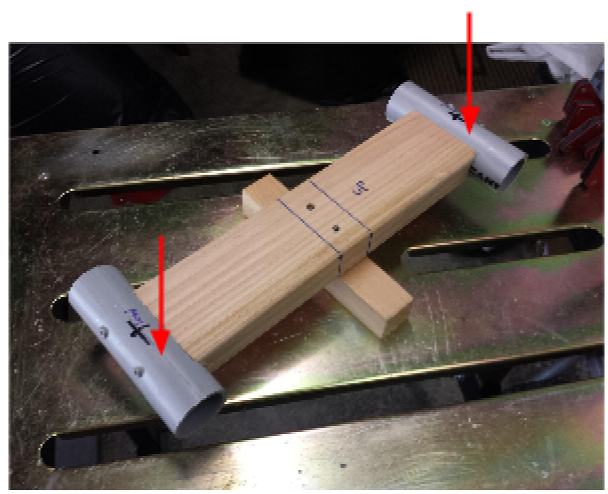
Appendix 8.2 Testing of Track-Tie Joint

The PVC rail to wood tie screwed joint was a feature of the track design which would be very difficult to analyze, so I decided to do some element level testing to determine this critical joint's load carrying capability. I devised several test elements, and took them to a professional mechanical test laboratory where load and deflection could be monitored.

Track-to-Tie Strength Tests



TTST-01-01 with load between screws



TTST-01-01-OS with load directly over screw

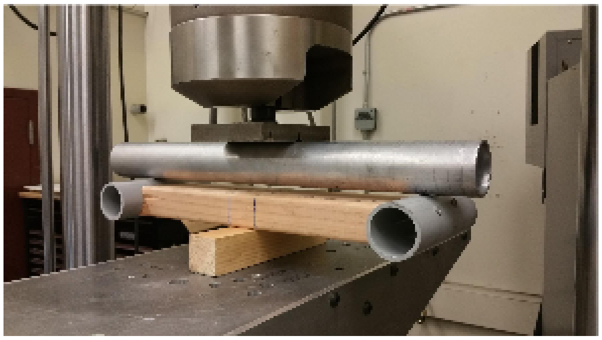
These are the first two test configurations, representing a loaded wheel over and in between the fasteners.

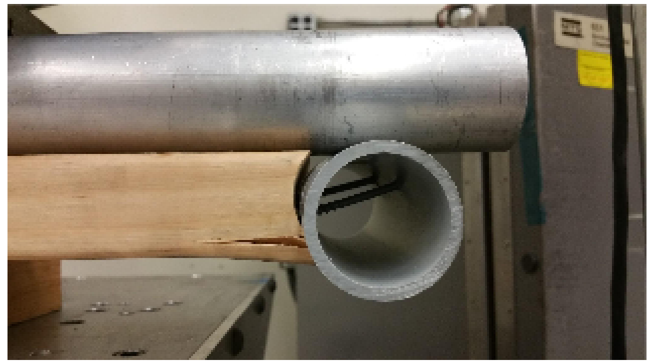
The test procedure was as follows:

- compression test on flat platen, with 2” round load bar touching two load points on PVC tracks
- load to 100#, return to zero, set deflection to zero
- record load and deflection
- note noises at loads
- hold and unload at first sign of non-linear behavior, note if deflection

returns to zero

- reload to next sign of non-linear response



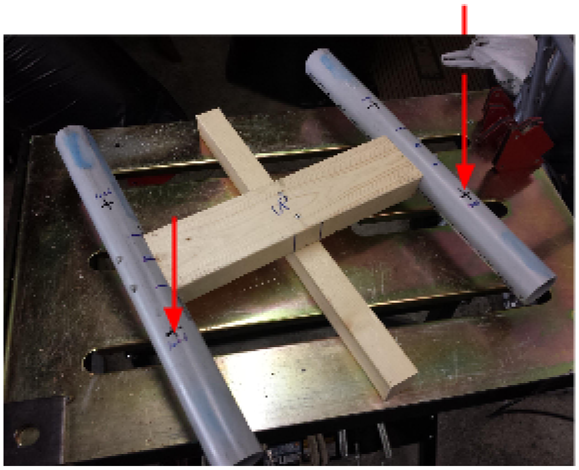


Specimen	Test Temp	Ult. Load (lbs)	Rate	Notes
TTST-01-01 between screws	72°F	1001	.1"/min	First crack heard at 820lbs
TTST-01-01b between screws	72°F	1135	.1"/min	1600lbs.
TTST-01-01-Over Screw	72°F	869	.1"/min	

Conclusion: when wheel is directly over one screw, that screw experiences more load and fails at a lower load than when the load is between two screws.

Track-to-Tie Strength Tests

TTST-02-01
Strength test with cupped tie ends

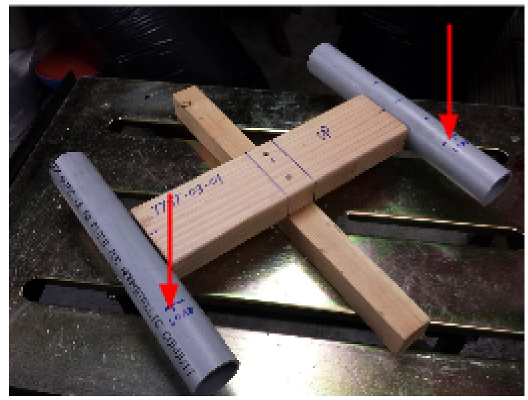


TTST-02-01 with load ¼ of the distance between ties (3.5 inches on a 15-inch tie separation) ¼ distance represents fixed-end beam bending between ties

Test procedure:

- same as 01-01, except load load bar is offset from center by 3.5 inches

TTST-03-01
Strength test with "standard" flat-end ties, (with no conforming "cupped" tie ends) for comparison. Track gauge identical at 15.25 inches.

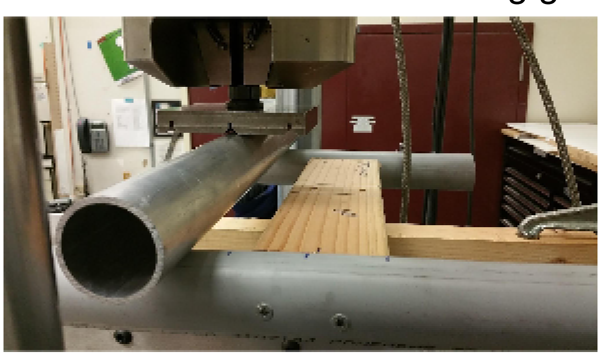


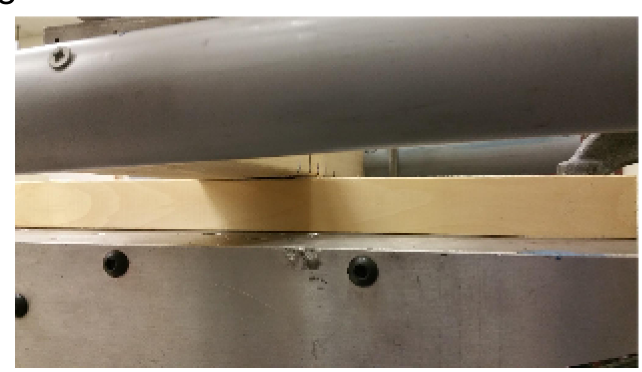
TTST-03-01 with load ¼ of the distance between ties (3.5 inches on a 15-inch tie separation) ¼ distance represents fixed-end beam bending between ties

Test procedure:

- same as 02-01

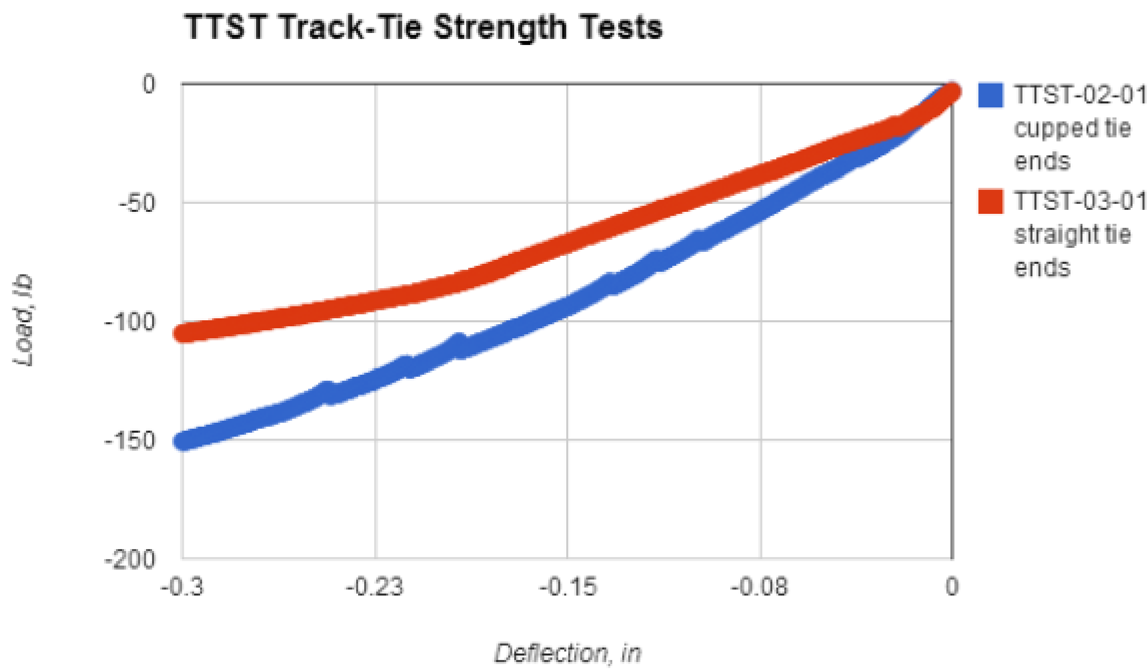
The next tests attempted to determine joint capability when the wheel loading was a critical distance away from the tie, and produced the maximum track moment loading going into the fasteners.





On both TTST-02-01 and TTST-03-01 tests, the moment due to the offset load was enough to pry the tie off of the supporting 2X2, so the ultimate strength of the PVC track-to-wood-tie was unable to be determined. However, we can compare relative initial stiffnesses for both cupped and flat tie ends.

This test configuration doesn't account for tie-to-tie bending tension strength/stiffness of the PVC rails, and therefore did not replicate the full up track assembly. A new, larger subcomponent test specimen must be devised.



Conclusion: Cupped-end ties are about 50% stiffer than flat-end ties
Note - only initial test results shown. Track-to-tie joint did not fail in either configuration, due to test setup.
Recommendation: I should repeat this testing, including specimens where the fasteners point 25 degrees up, as well as down, and include specimens using 3 fasteners. I should include fatigue testing next time as well, which could take some time. If I want a BYRC to last 15 years, and it is ridden 100 times a month, that's a total of 18,000 cycles. Commercial aircraft are designed to take 3.5 lifetimes, so I would test to 3.5 X 18,000 = 63,000 fatigue load cycles, which I'll say is 2/3rds of limit load. If load could be applied twice a second, then 63,000 cycles would take 9 hours for each test. I might find I need better screws. I'll give it more thought, but even some initial "ballpark" fatigue testing would establish a rough fatigue limit.

✂••••••••••••••••••••

About the Author

Paul Gregg is father of four, grandfather of six, and a retired engineer. He had a childhood love of all things mechanical. He visited his grandfather's remote ranch in Wyoming where he was exposed to a life of mechanical wonders, from tractor hydraulic lifts, to an huge hay threshing machine a.k.a. spaceship to the moon. He dis- and re-assembled nearly every mechanical object in the Gregg household, with varying results. His favorite toys were a 1960's Gilbert Erector Set, with a powerful geared electric motor, and a Wilesco D1 single-acting-piston live steam engine, which he played with until the boiler burned through. When the carnival came to town, he was the kid looking under the rides at the whirling gears. Paul earned a Bachelors of Science degree in Mechanical Engineering at the University of Utah. His career at The Boeing Company centered mainly on development of advanced aerospace structures of composites and titanium, advancing the processes of welding and adhesive bonding. He was made an Associate Technical Fellow and holds 29 US and foreign patents, two special invention awards, and was Boeing Aerospace Engineer of the Year in 1988. His career touched a wide variety of aerospace programs, including short range missiles, large launch vehicles, space structures, hypersonic vehicles, military fighters, military transports, supersonic laminar flow control flight experiments, and a variety of new structures on commercial aircraft floors, empennage, and engines on the 787 and 737MAX. Paul and his wife Debbie are prolific world travelers, and Paul's idea of a perfect souvenir is a miniature stirling cycle engine from Germany, a DaVinci clock from Italy, a putt-putt boat from Holland, or a toy steam engine from England. He currently owns and operates three backyard roller coasters with the help of his grandchildren.

Online Resources:

http://backyardrollercoasters.org/

Built a coaster? Share it here and let's build a community of enthusiasts!

http://reddit.com/r/backyardcoasters

YouTube Channel:

https://www.youtube.com/user/psg20101