ROSE-HULMAN GRAND PRIX ENGINEERING

RPG008 Laptime Simulation Analysis

July 2018

Thad Hughes - hughest1@rose-hulman.edu

Derek Beck - beckda@rose-hulman.edu

Andrew Novotny - novotnaj@rose-hulman.edu

1. Motivation

RoseGPE is a student design competition team at Rose-Hulman that competes in the Formula SAE competitions, typically at the Lincoln and Michigan events. RoseGPE is driven by students learning and gaining work experience, and does this by aiming to score high at competition. To do this, the team builds a new prototype vehicle every year.

The competition is historically composed of ⅜ ‘static’ events (cost judging, design judging, business case judging) and ⅝ ‘dynamic’ events (acceleration, skidpad, autocross, endurance, and fuel economy)- meaning there are many facets to earning points and doing well.

Lap Time Simulation can be utilized to determine the configuration of vehicle which can produce the most points at competition. Determining points outcome from the acceleration, skipad, autocross, and endurance events is largely straightforward.

Determining points outcome from fuel economy can be determined by keeping track of the kinetic energy delivered by the powertrain, and correlating this, but unless efficiency factors are actually introduced, this does not allow for analyzing the efficiency of a powertrain, but only the energy consumption of the vehicle.

Determining points outcome from the cost event is also possible but not in the scope of RoseLap. Determining points outcome from the business case event is less straightforward. Design points are based around the proper engineering design of the vehicle, and is more a judgement on how everything was done, so is not to be considered when determining high-level vehicle goals.

2. Available Parameters and Questions to Answer

We have two models at our disposal. The first is the ‘point mass’ model. This has the following parameters, used as follows:

1. Aerodynamic forces
    a. The forces are provided at 35MPH as this is what the aero team uses as a benchmark. The actual force used is a square relationship that passes through this datapoint.
    b. For both drag and downforce, a value must be provided for a DRS setting, ‘airbrake’ setting, and normal setting.
2. Tire parameters
    a. In x- and y- directions, the maximum force that can be provided is linear with respect to the normal force. This means there is an offset and a slope, modeling the diminishing returns of additional normal force.
        i. These parameters are per tire- the fact that a vehicle has 4 tires is taken care of by software, not the input parameters.

    ii. In multiple directions, the maximum force allowable is an ellipse; a ‘friction ellipse’
3. The mass of the car is a point-mass, with only the overall mass as a parameter.
4. Engine
    a. The engine power is linearly interpolated from torque and RPM datapoints.
        i. At RPMs lower than the range of RPMs specified, the output torque is equal to the lowest.
        ii. At RPMs higher than the range of RPMs specified, the output torque is zero.
5. Drivetrain
    a. A list of gear ratios is accepted which can be shifted between sequentially
    b. A final drive ratio is accepted.
    c. It takes a certain amount of time for a shift to occur, which is specifiable.
        i. Shifts occur when the vehicle is accelerating and not traction limited, and another gear would provide more wheel force.
        ii. After braking, the best gear is selected, regardless of the previous gear

Questions to be answered with this model are:
- What tire is best to use? (This question is actually more complicated and beyond the scope of Lap Time simulation, but gives us an idea of how important tires are)
- What is the points benefit of reducing mass?
- Which engine / engine configuration should we run?
- Which final gear ratio should we use?
- Should we skip or change the spread of the transmission?

The second model available is the ‘two tire’ model. This model is less stable than the point-mass and uses significantly more computational power so should be used sparingly and the results should always be investigated to check sanity. This has the following additional parameters and behaviors:
1. Aerodynamic forces
    a. The center of pressure may be specified. Currently, this is the same for all configurations.
2. The mass of the car is still a point-mass, but has specifiable center of gravity height/longitudinal position and wheelbase length.

Questions to be answered with this model are:
- What is the optimal CP location?
- What is the optimal CG location?
- Are additional aerodynamic modes feasible or helpful to performance, and by how much?
- What aerodynamic targets should be chosen?

Questions we want to answer, but cannot with these models as they stand:

- Should we run a CVT?
- What differential settings should be used?
- What suspension configuration should be used?
- How is the drivability of the car affected by all of these parameters? (In other words, sensitivity to driver inputs)

3. Tracks to run on

We should run a configuration of a car through both an entire Lincoln and entire Michigan competition. Obviously, though, there is some variation in the tracks from year-to-year. Michigan 2018 endurance was also notably long, but arguably redundant, and as such, it would be possible to run perhaps half of the track and achieve the same results at significantly less computational expense. I propose running 4 different competitions in entirety.

- Michigan 2017
- Michigan 2018
- Lincoln 2015
- Lincoln 2018

Tracks generated before were arcs and lines traced from track maps. We could do the same thing, but with splines. This would require rewriting the segmenter. We should do this and then examine the effects on simulations.

4. Gathering Data

For tires: The first step is to perform tire data fitting as described in the RoseLap v4 analysis. See the spreadsheet “Tire Fitting Results”.

For engine:

The CO2 factors are listed in the 2017-18 FSAE rules:
Unleaded petrol / gasoline: 2.31 kg of CO2 per litre
E85: 1.65 kg of CO2 per litre

The ‘efficiency factor’ is the amount of mechanical energy produced by a unit of fuel. This value is calculated/correlated by simulating RGP005 around the Lincoln endurance track (for all 15 laps) to determine the mechanical energy production (14462010 ft*lbf), and dividing this by the amount of fuel used (4.16 Liters). This number can be scaled to study the effects of increasing the efficiency of the engine. As such, it is important to note that this number only applies to a naturally aspirated YFZ450R running with 100 octane fuel. This parameter should be evaluated if other configurations are to be studied.

We also created a 'supercar' to create baseline lap times for tracks on. The purpose of this is to get apples-to-apples comparison of simulation vs. simulation. This 'supercar' has Stuttgart's CBR600RR engine, weighs 450 pounds with driver, and has an aero kit with 90 lb of downforce at 35MPH- combining the best aspects of Berkley circa 2013, Stuttgart circa ????, and some of the old FSAE cars with massive aerodynamic kits. This baseline car was swept over a range of gear ratios.

Track	Time (s)	CO2 emissions
acceleration.dxf	3.487	-
mi_2018_autox.svg	45.741	-
mi_2018_endurance.svg	78.342	0.8166
ne_2015_autox.svg	44.594	-
ne_2015_endurance.svg	67.041	0.6811
skidpad_loop.dxf	4.169	-

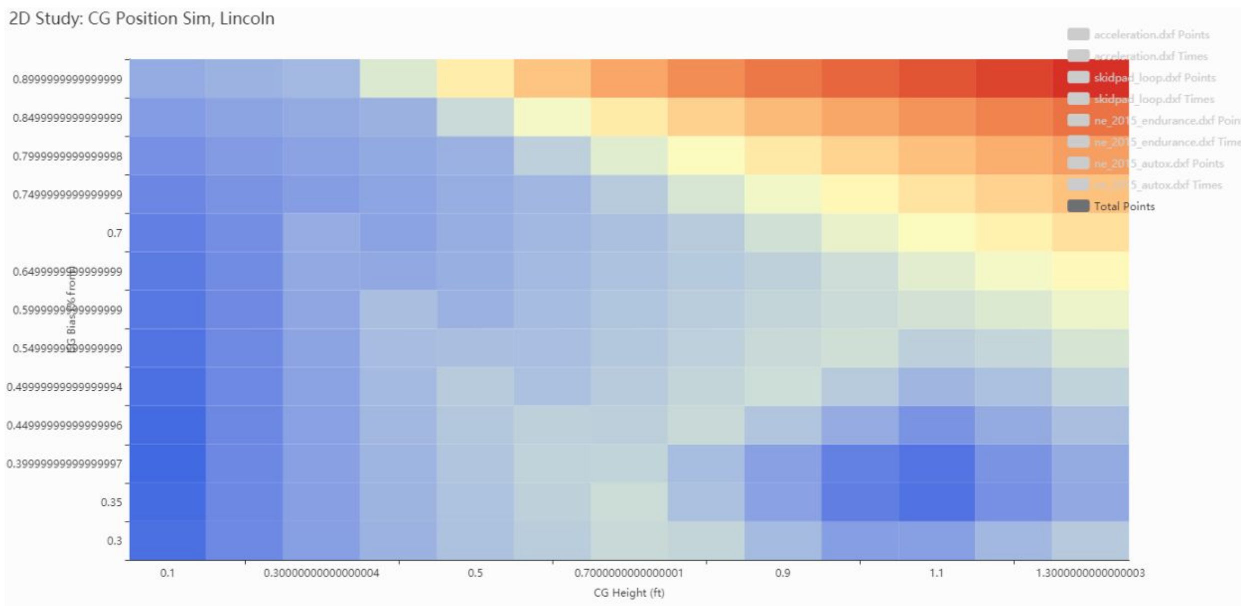
SS Models:

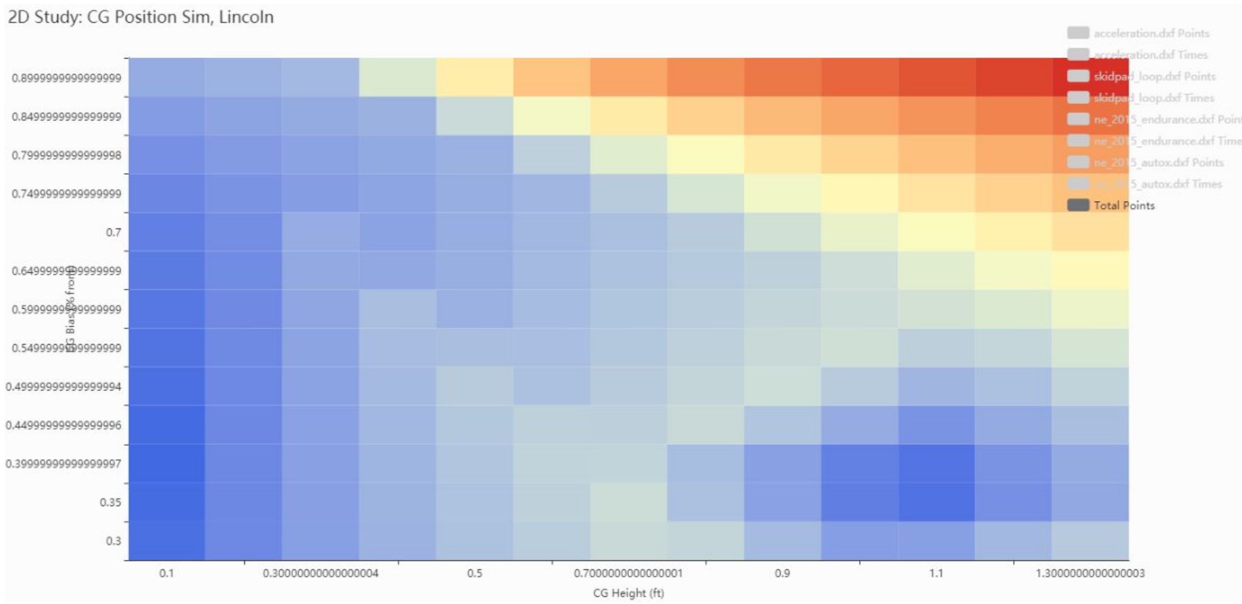
	Time (s)			CO2		
Tires	1	2	4	1	2	4
skidpad_loop.dxf	3.8813	3.9657	4.6410	0.0057	0.0176	0.0365
acceleration.dxf	3.3537	3.3596	3.3596	0.0669	0.0672	0.0672
mi_2017_autox.dxf	42.1180	42.5090	47.2737	0.4385	0.4386	0.4601
mi_2017_endurance.dxf	57.8619	57.6379	64.0827	0.5800	0.6464	0.6767
mi_2018_autox.dxf	48.4686	49.1484	55.3027	0.4760	0.5198	0.4990
mi_2018_endurance.dxf	86.4798	88.1015	100.3315	0.7334	0.8410	0.8941
ne_2013_autox.dxf	42.4513	43.2368	48.7629	0.4209	0.4268	0.4162

ne_2013_endurance.dxf	55.1117	56.7935	64.7961	0.5634	0.6208	0.6123
ne_2015_autox.dxf	45.8889	47.0780	53.5565	0.4554	0.4793	0.4855
ne_2015_endurance.dxf	65.0384	66.9977	76.3971	0.6452	0.6862	0.7414

5. CG Position

We swept CG position (height and bias) over a realistic range of values. Front and rear roll stiffnesses are held constant.

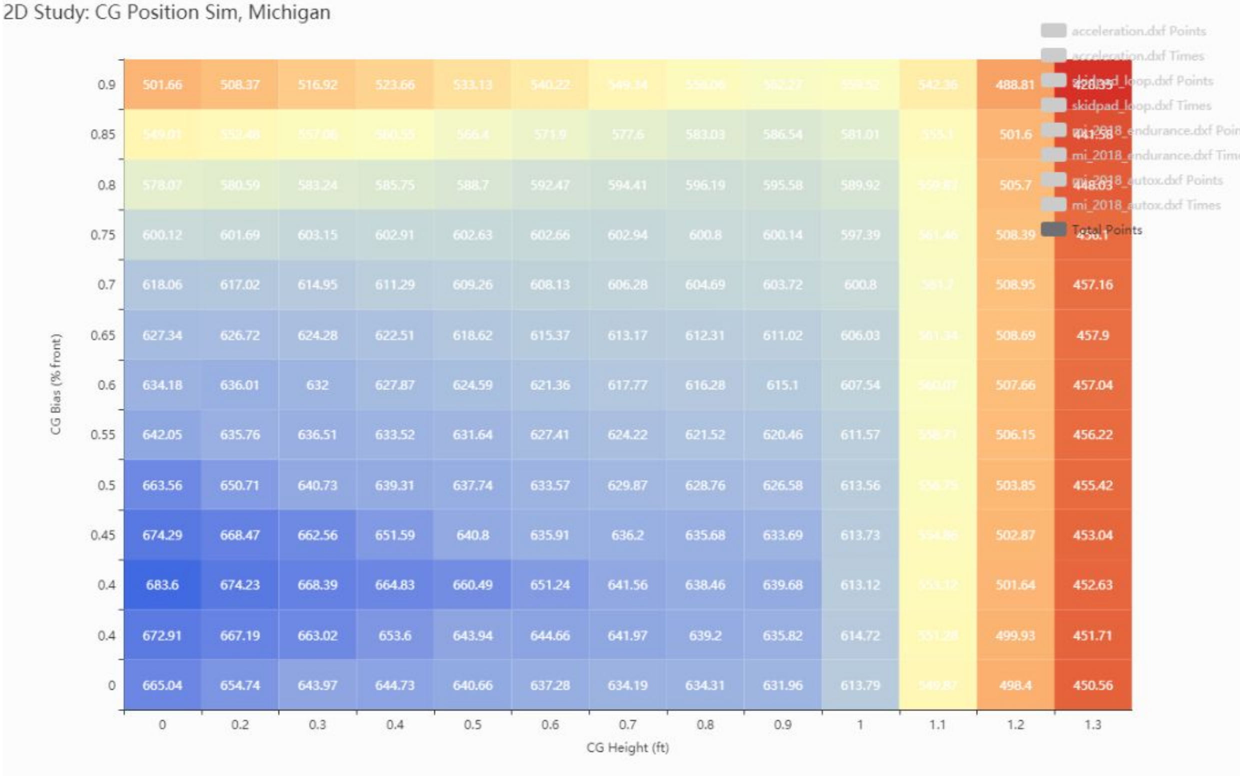




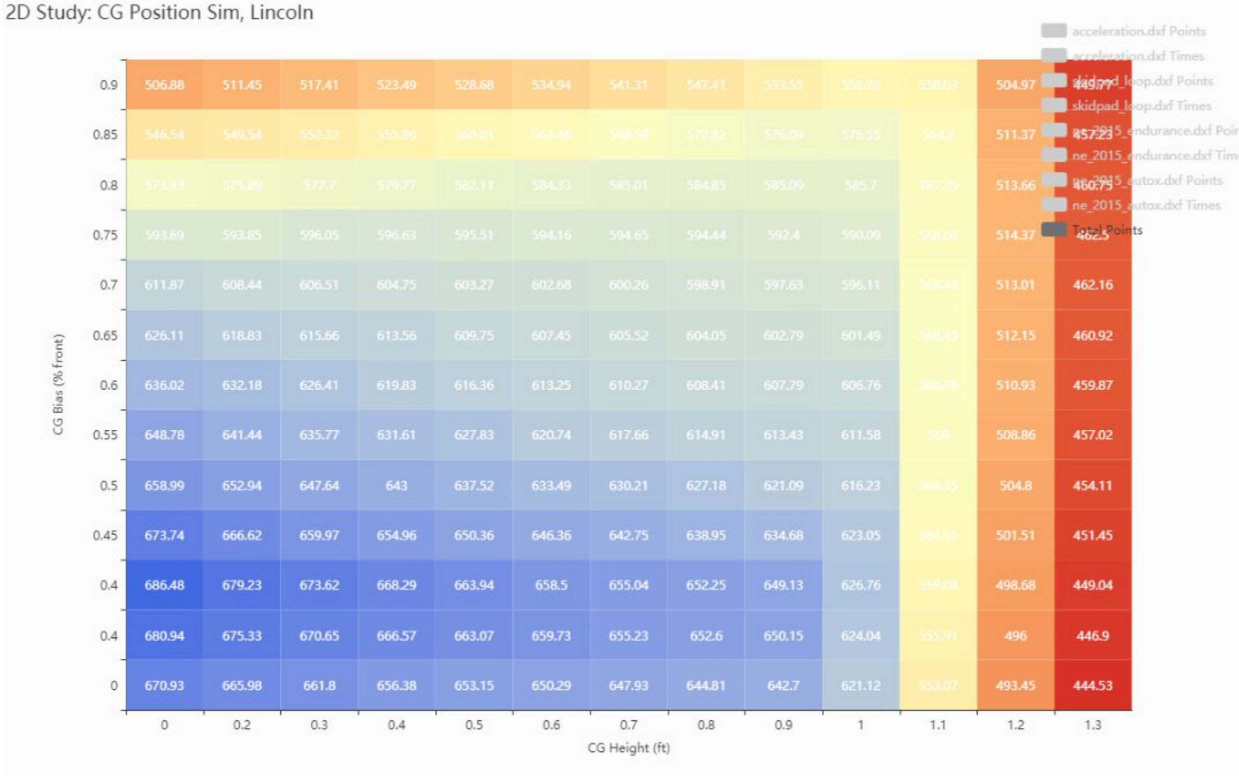
These results are dubious and defy conventional wisdom. Typically, one should expect that decreasing CG should boost points. This does somewhat line up with the tire models used, however- the total grip is independent of lateral load transfer (but does depend on its distribution). The end conclusion does, however, reinforce the targets picked- with a realistic CG (0.9-1.1 ft), we should shoot for a front weight bias of 0.35-0.4. Conventional wisdom is (for a car with the same front and rear tires) to aim for 0.4-0.45, as this balances the 50-50 ideal for corners, and rear ideal for drive/brake (for a RWD car).

The sim was re-ran, this time forcing the LLTD to be 5% more rearward than the static weight bias.

2D Study: CG Position Sim, Michigan



2D Study: CG Position Sim, Lincoln



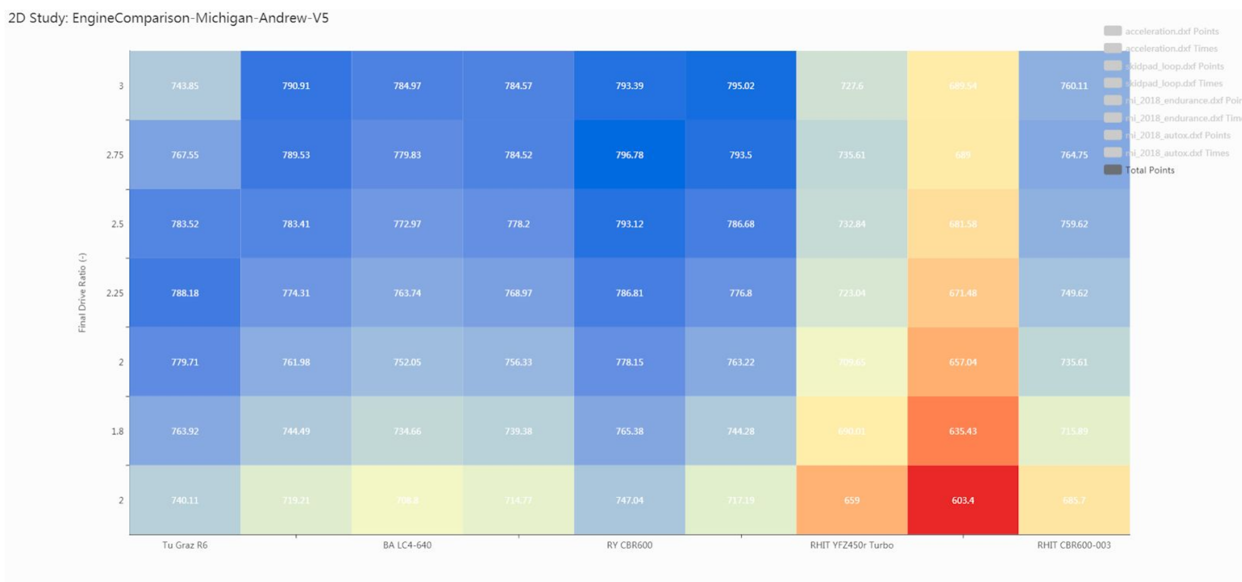
This shows that the CG bias should be around 0.4, and CG height minimized (about 6 points per inch until the CG height rises above 1 ft, at which point the points drop off tremendously). This hinges on the tire models used though.

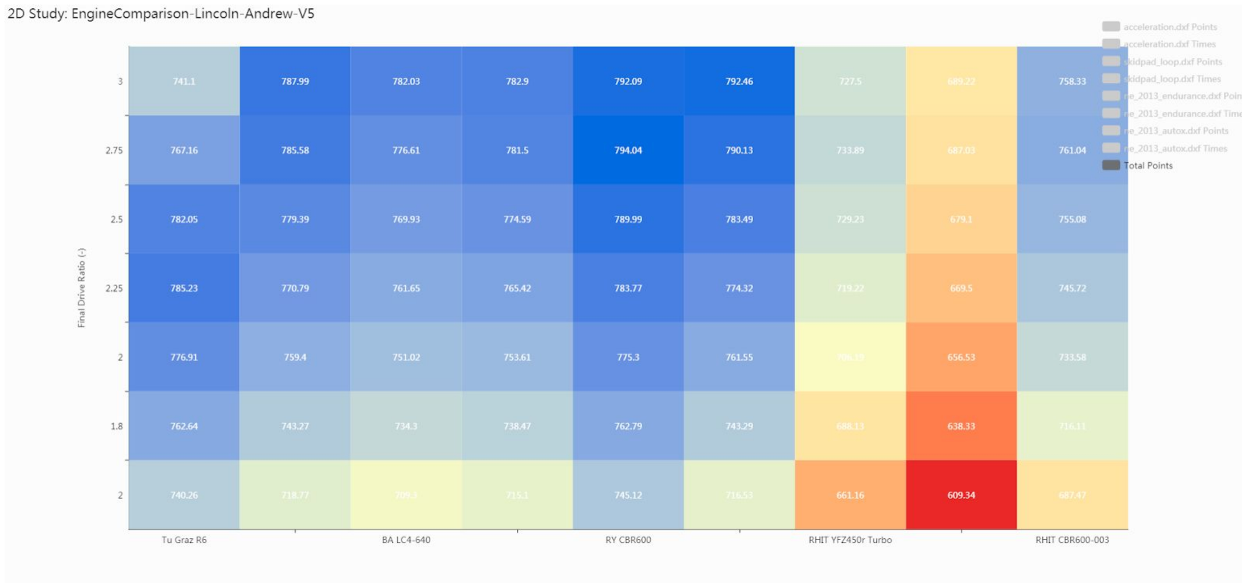
6. Track Width

Based on this, there is a line at which things get very bad, but otherwise, there isn't a real optimum.

7. Engine Comparison

The purpose of this study was to seek confirmation that our YFZ450r setup with turbo is the best option for FSAE competition. Data for this study was gathered from http://www.fsaesim.com/downloads/torquecurves.xlsx as well as our dyno pulls completed this winter. Using RoseLap, we carried data from the excel sheet into YAML format so it is able to be interpreted by RoseLap. We carried torque at different RPM, gear ratios, and an estimated car weight with the various engines to fill the X-axis while performing a sweep of values to find the optimal drive reduction (in order to receive the most accurate results).

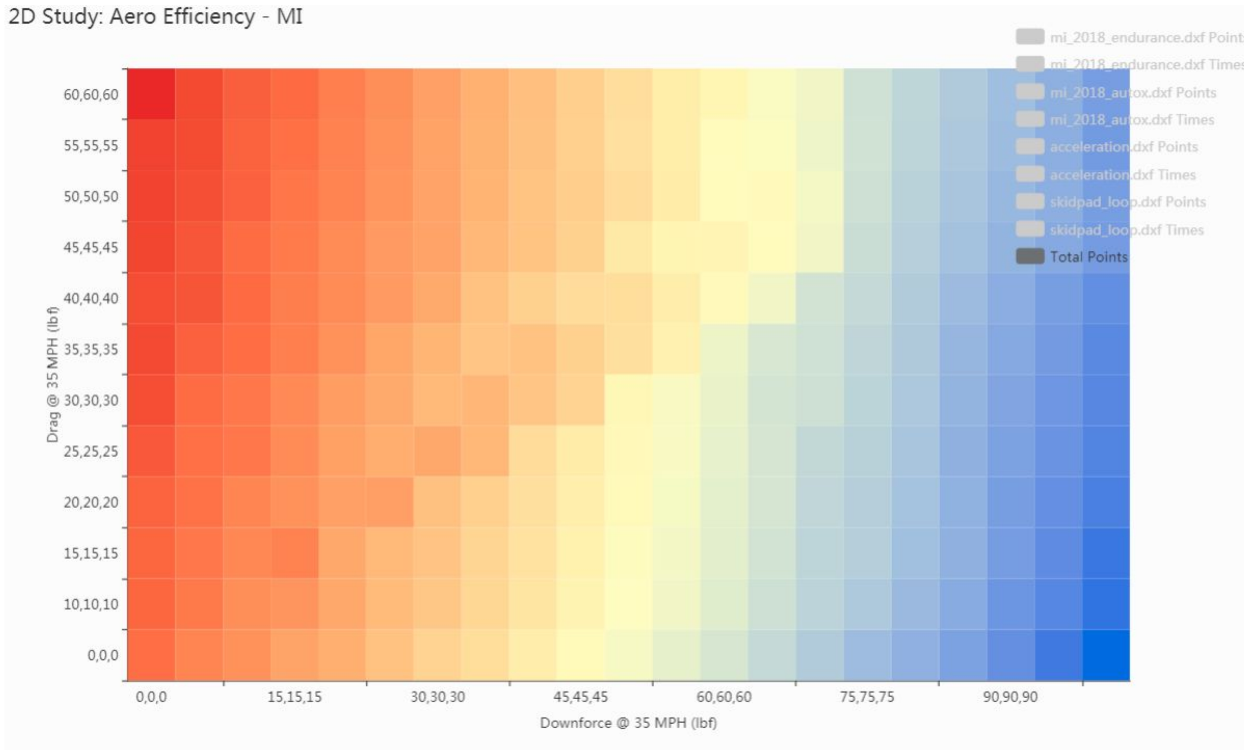




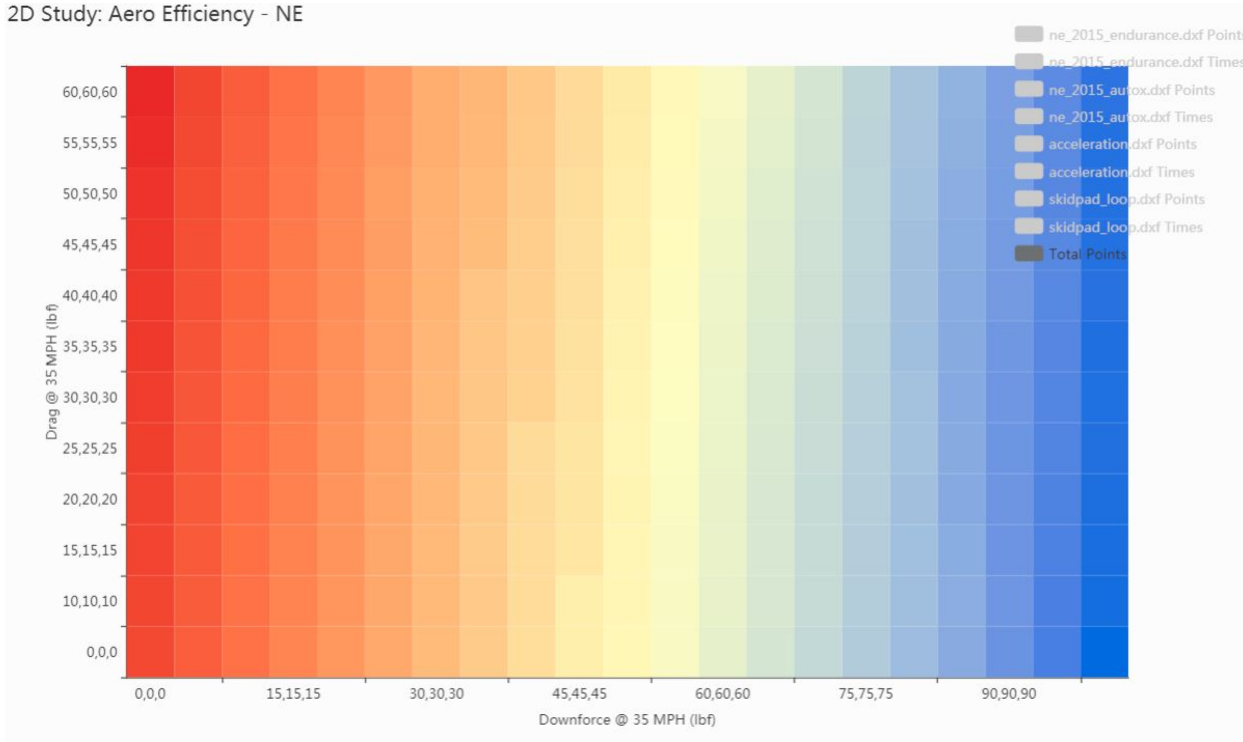
Our CBR tune seemingly is better by 30 points than the current turbocharged setup. Other teams' more dialed in setups seem 30 points above that.

8. Aerodynamic Efficiency

We simulated the baseline car with varying drag and downforce for both the MI and NE competitions. The results:



Downforce	Drag	Pts Overall	Downforce	Drag	Pts Overall	Pts/Downforce	Pts/Drag
0	60	486.4	100	60	560	0.736	-
0	0	496.9	100	0	571.5	0.746	-
						0.741	-
100	60	560	100	0	571.5	-	-0.192
0	60	486.4	0	0	496.9	-	-0.175
						-	-0.183
						Downforce/Drag Break Even	4.042

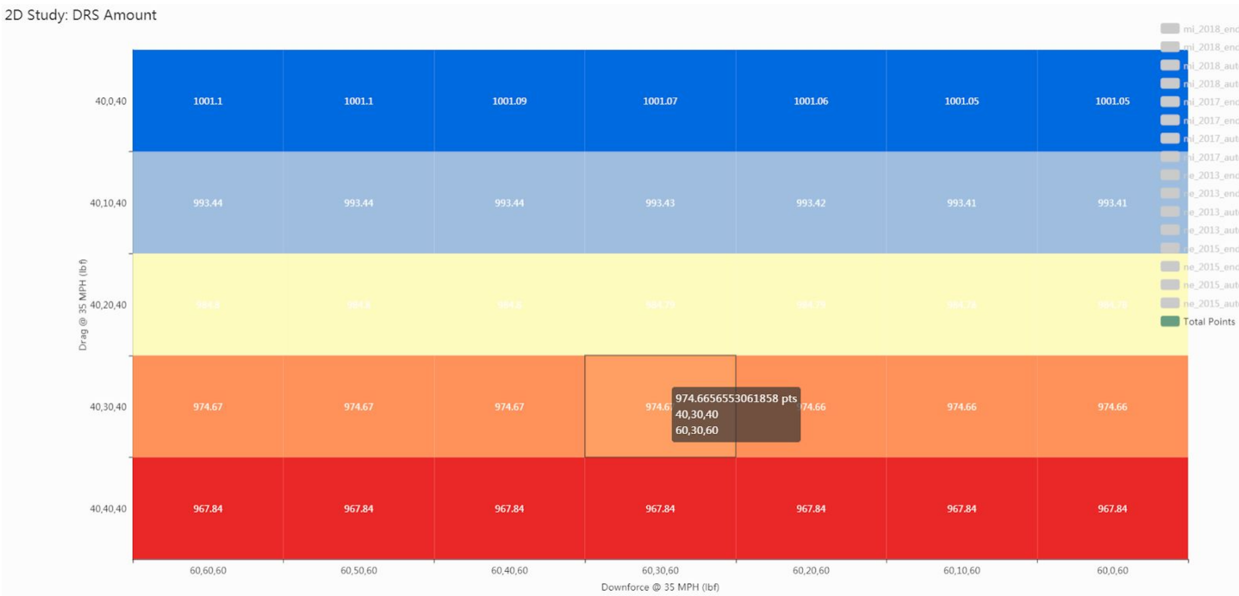


Downforce	Drag	Pts Overall	Downforce	Drag	Pts Overall	Pts/Downforce	Pts/Drag
0	60	476.4	100	60	584.5	1.081	-
0	0	481.6	100	0	587	1.054	-
						1.068	-
100	60	584.5	100	0	587	-	-0.042
0	60	476.4	0	0	481.6	-	-0.087
						-	-0.064
					Downforce/Drag Break Even		16.636

Conclusion: drag is relatively unimportant (about 4x less important at MI, and nearly irrelevant at NE). At Michigan, the point value of downforce is slightly less than at Lincoln.

9. DRS Study

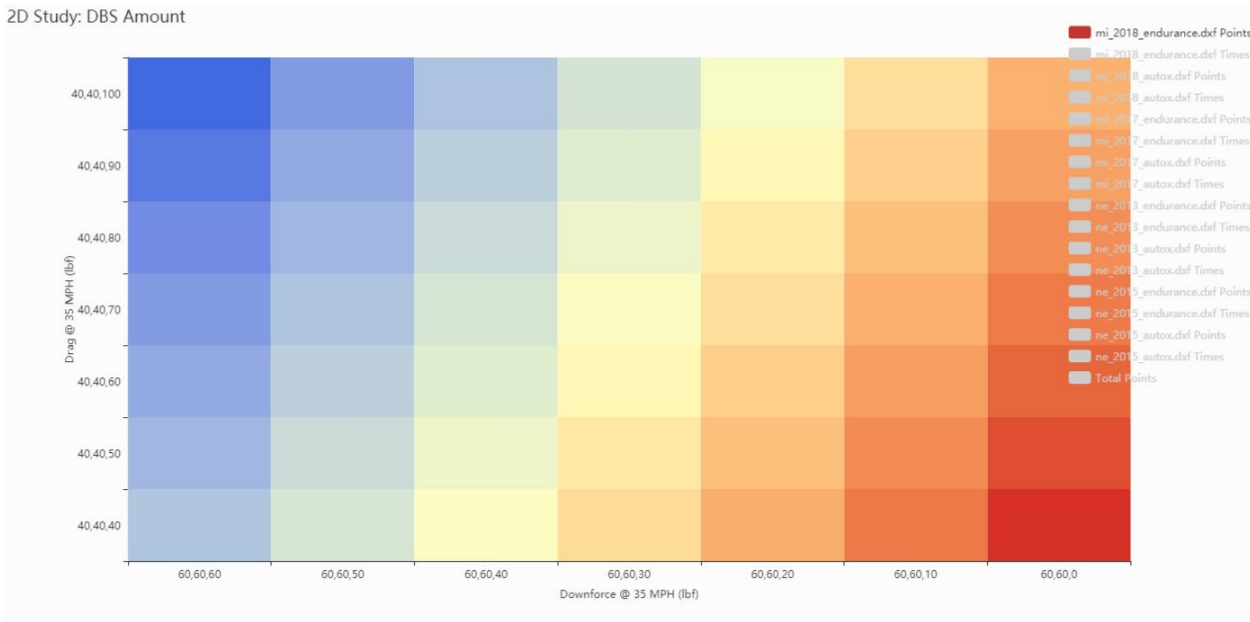
A sweep was made for the DRS Downforce and Drag to see what targets might be desirable out of such a system.



The total benefit across the autocross/endurance tracks at 8 competitions is 33 points, or an average of 4.2 points per competition, for making a DRS system (which seems to not depend on the amount of downforce produced when enabled). The points gain from a DRS system are small, but attainable..

The total benefit across the autocross/endurance tracks is 4.45 points, or less than half a point per competition for making a DBS system that provides the same downforce

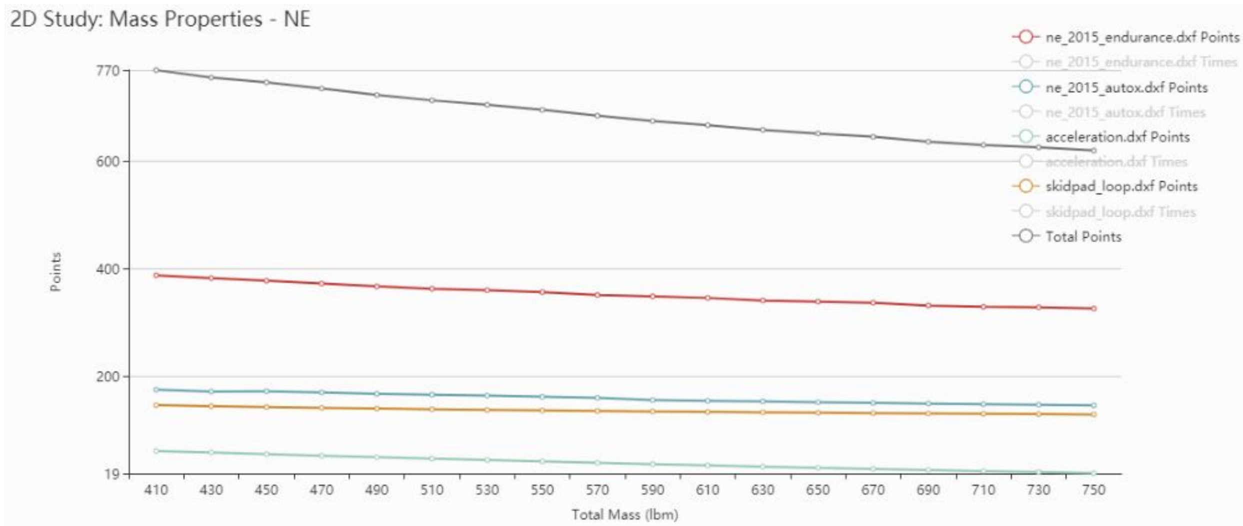
10. DBS Study

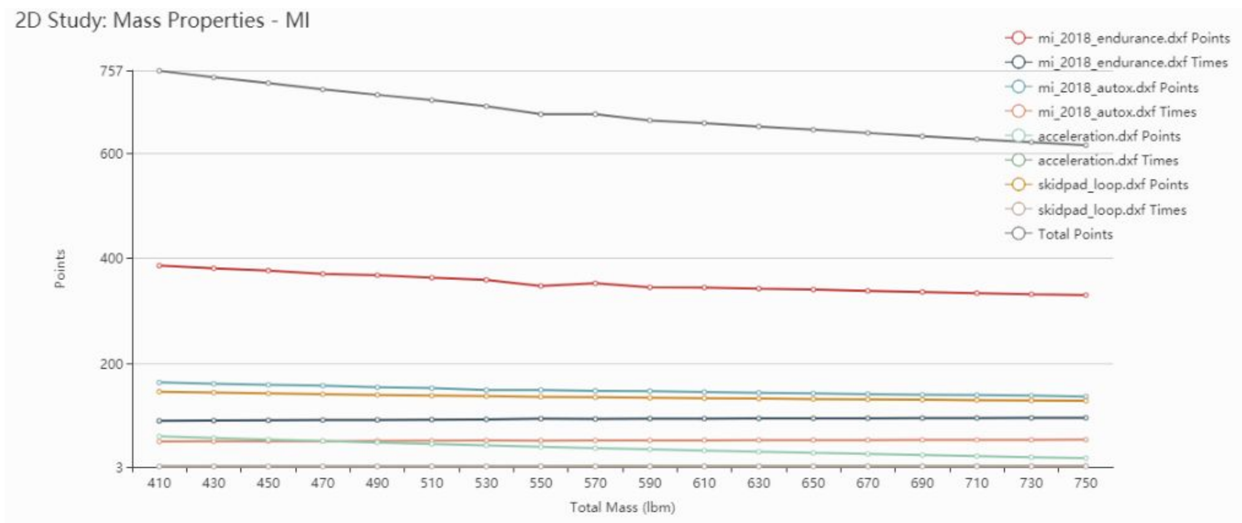


Description	DBS DF	DBS Drag	Points in all autoX events
Ideal DBS	60	100	280.120
No DBS	60	40	279.945
Bad DF DBS	0	100	279.423

It is fairly easy to see that there is little benefit to be had in a DBS system, unless amounts of drag orders of magnitude larger than proposed can be made without sacrificing downforce. Sacrificing downforce severely harms braking capability more than additional drag can make up for it.

11. Dead Weight

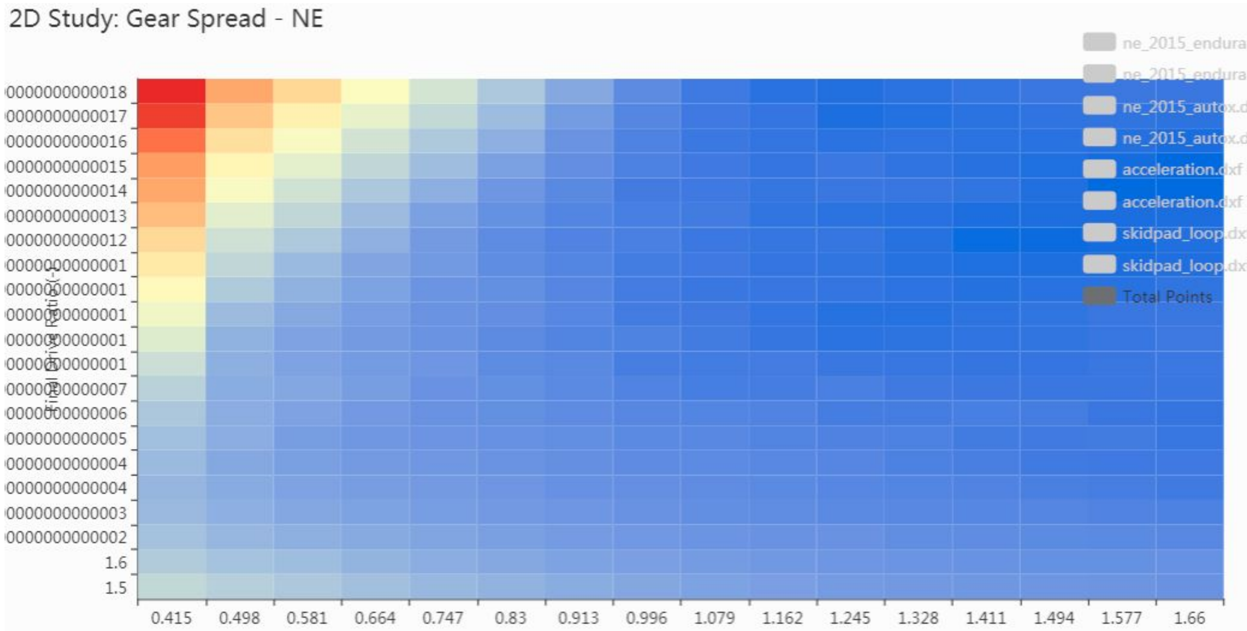




Sweeps were made to compare dead weight importance. There is some noise, of course. Overall, about 4-5 points at each competition can be gained by cutting mass by 10 pounds.

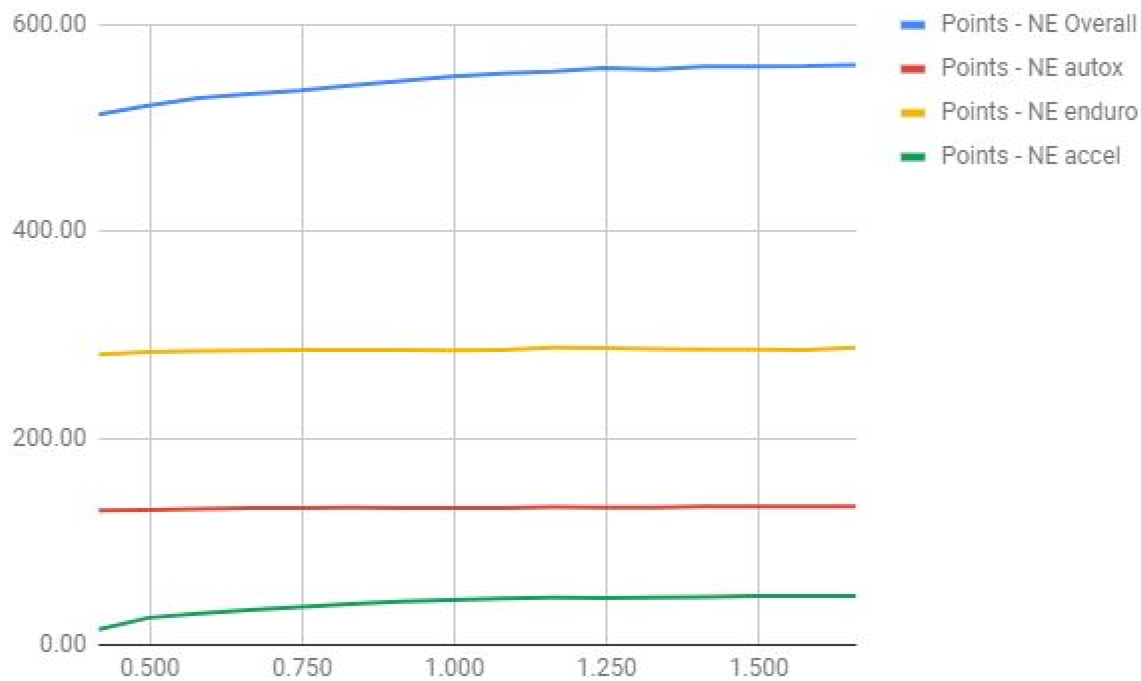
12. Gear Spread

The gear spread for the YFZ450R is investigated. Gear spread in this case is defined as the difference between the maximum and minimum ratios.



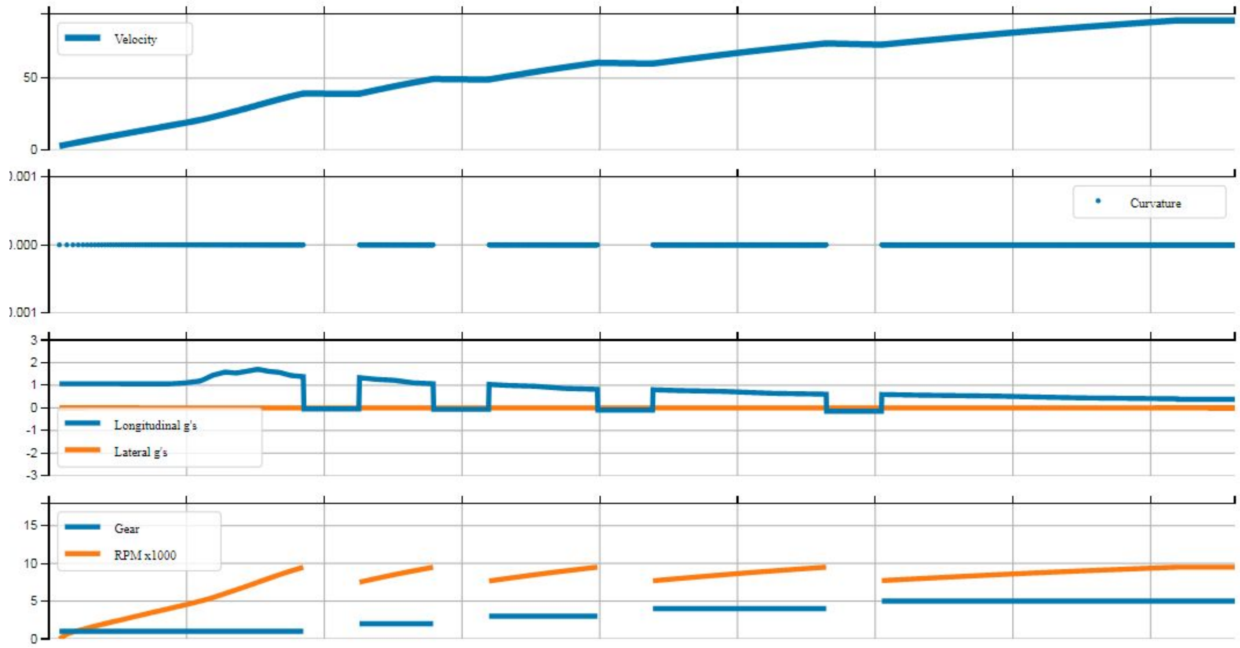
These are the point gains from each event at the optimal gear ratio as a function of gear spread. The YFZ spread is bolded.

Spread	Points - NE Overall	Points - NE autox	Points - NE enduro	Points - NE accel
0.415	513.46	130.16	281.21	15.10
0.498	522.27	130.81	283.52	26.28
0.581	529.46	131.78	284.68	30.61
0.664	533.42	132.56	284.84	33.93
0.747	536.70	132.57	285.39	36.91
0.830	541.42	132.80	285.25	39.47
0.913	545.67	132.34	285.65	41.84
0.996	550.39	132.43	284.96	43.67
1.079	553.31	132.54	285.43	44.96
1.162	554.91	133.54	287.77	45.71
1.245	558.50	133.22	287.31	45.35
1.328	557.26	133.18	286.37	46.03
1.411	559.84	134.16	286.16	46.61
1.494	560.13	134.08	286.03	47.14
1.577	560.19	134.15	285.66	47.42
1.660	561.46	134.11	287.68	47.39

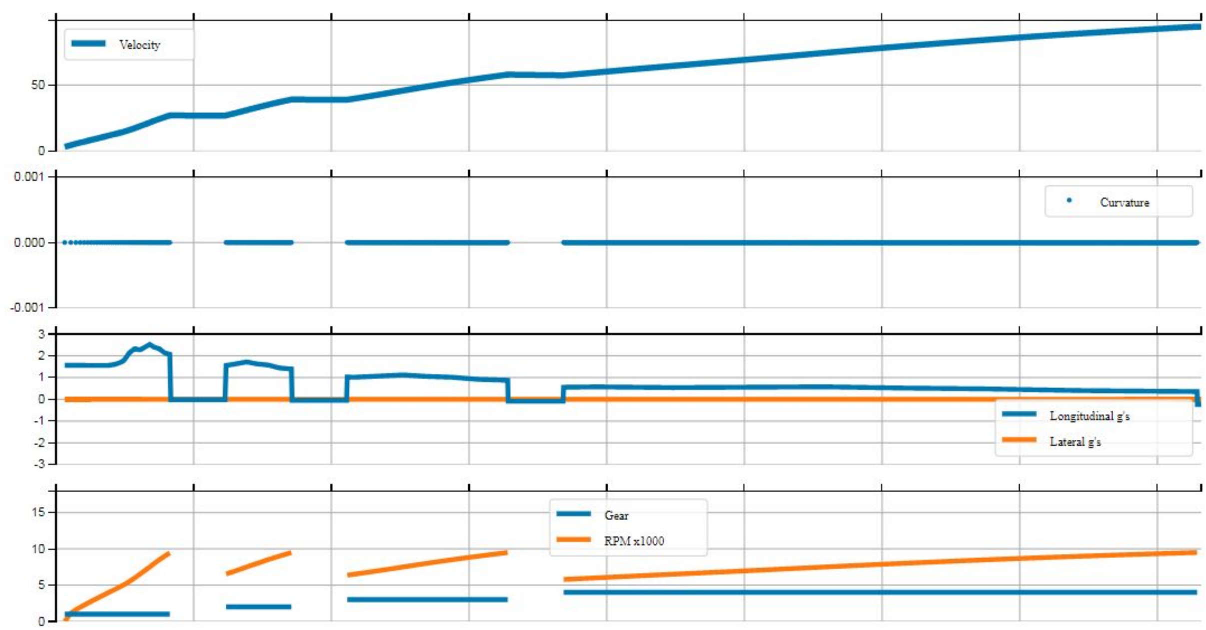


The benefits for a higher gear spread mostly appear in the acceleration event, and occur quickly- nearly all the benefits are realized by increasing the spread to around 1.245.

How does this occur? Here's an acceleration run with the stock spread:



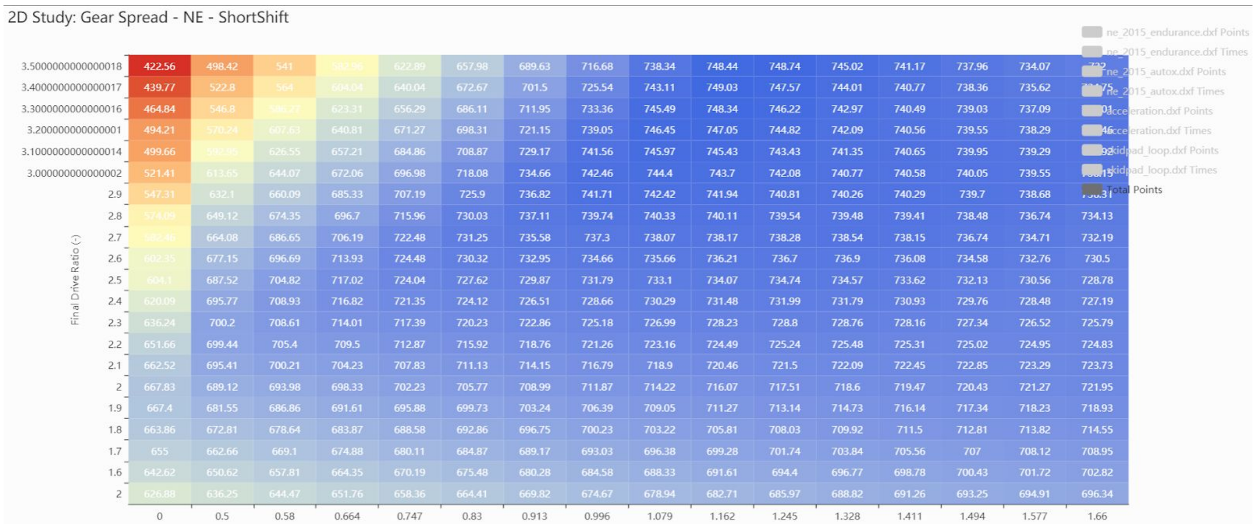
With an increased spread of 1.660:



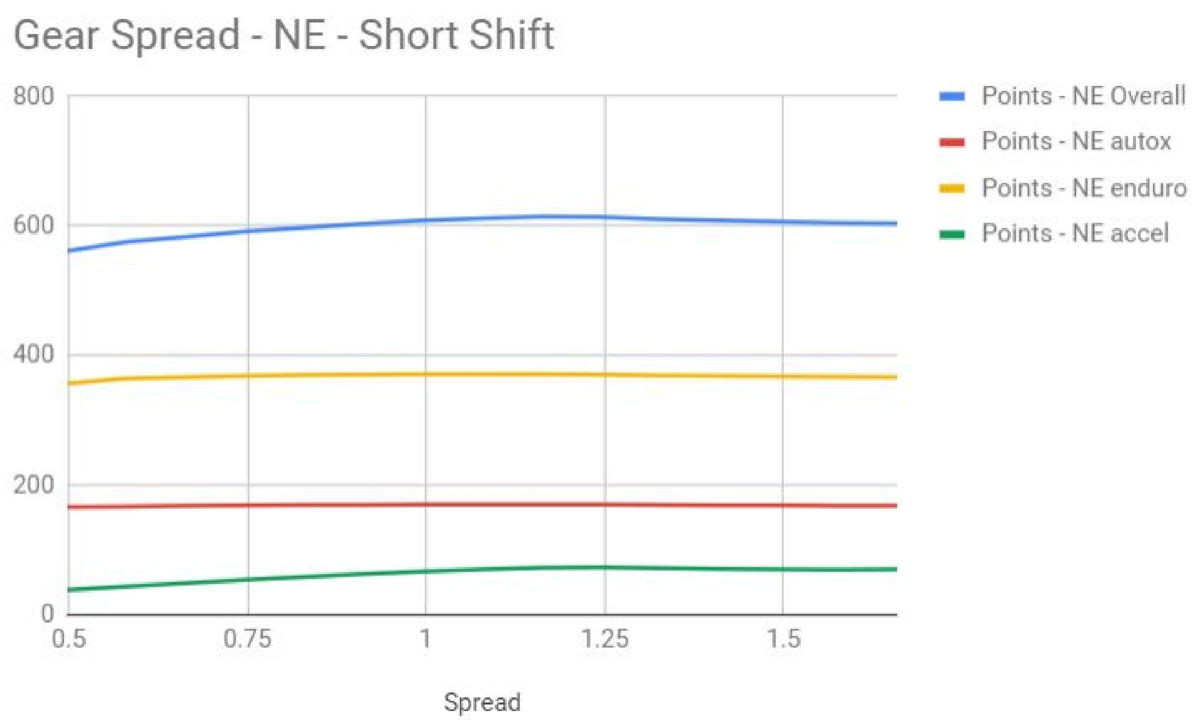
The first obvious thing to notice is that the increased spread uses one less gear! The other thing to notice is the engine RPMs are overall kept lower.

There is some potential here- but it would require significant investment to make these changes to the YFZ gearbox. Perhaps there is a different way to achieve these benefits...

Looking at the information above and seeing less gears being faster, it was deemed worthwhile to see whether similar results would be obtained with shift time set to 0.0 seconds. The chart can be seen below.



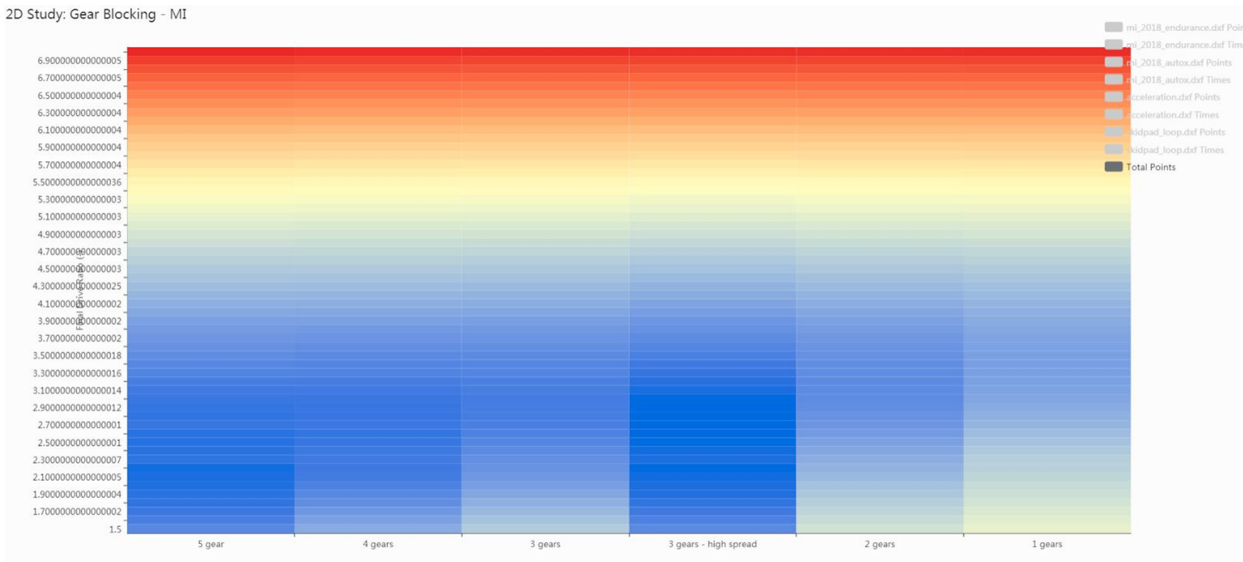
Spread	Points - NE Overall	Points - NE autox	Points - NE enduro	Points - NE accel
0.498	561.1	166	357.1	38
0.581	575.4	167	364.9	43.5
0.664	583.23	167.9	366.5	48.83
0.747	591.31	168.6	368.85	53.86
0.83	597.43	169.2	369.7	58.53
0.913	603.11	169.7	370.6	62.81
0.996	608.13	170.1	371.2	66.83
1.079	611.85	170.3	371.4	70.15
1.162	614.33	170.3	371.23	72.8
1.245	613.5	169.9	370.45	73.15
1.328	610.43	169.3	369.14	71.99
1.411	608.35	169.1	368.6	70.65
1.494	606.3	168.8	367.8	69.7
1.577	604.24	167.9	367.13	69.21
1.66	604	167.9	366.4	69.7



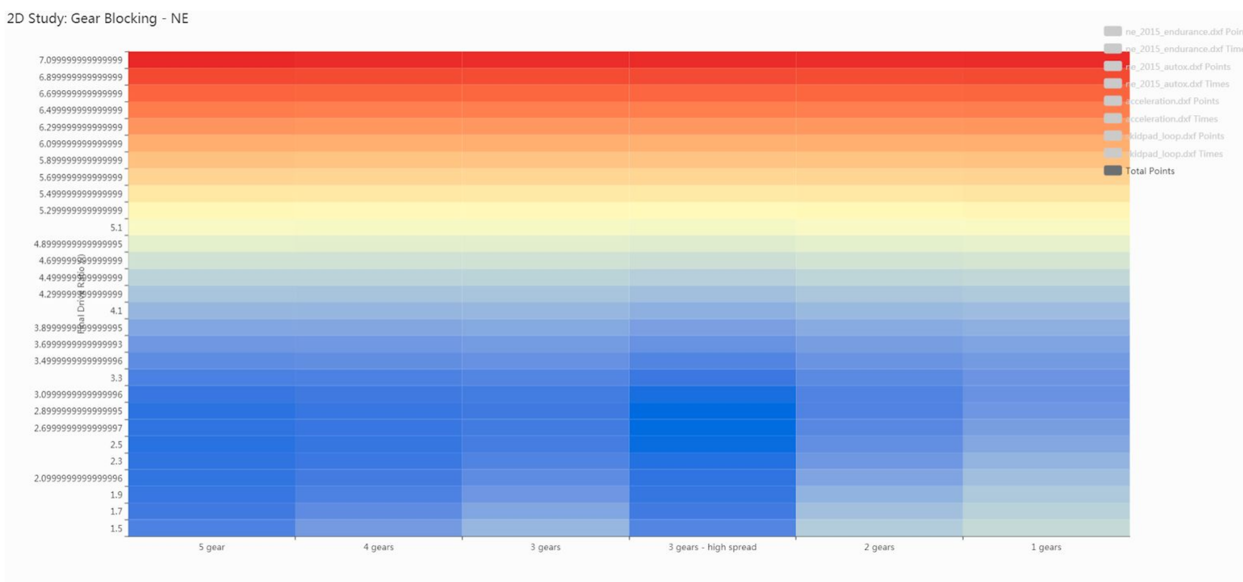
Looking at the charts gathered from the study, reducing the shift time lowers the optimal spread to approximately 1.162. Only thing that may mess up the data would be on the higher spreads favoring a larger reduction (some points were on the edge of the data gathered). Otherwise, I reach a similar conclusion to Thad's.

13. Gear Blocking

There is some potential here- but it would require significant investment to make these changes to the YFZ gearbox. Perhaps there is a different way to achieve these benefits...



Max: 543 (in 3 gears), next max: 541 (in 1 gear), min: 45

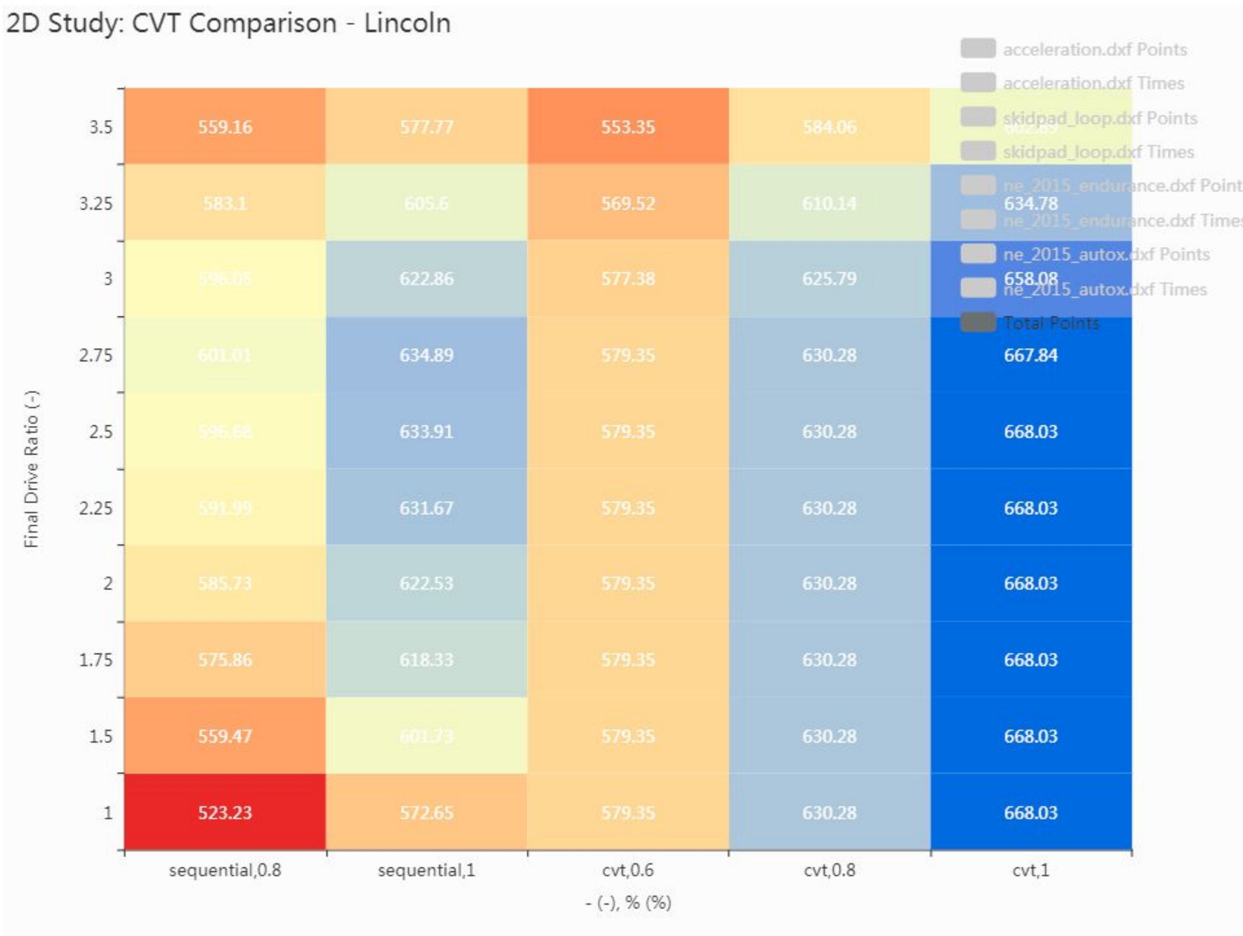


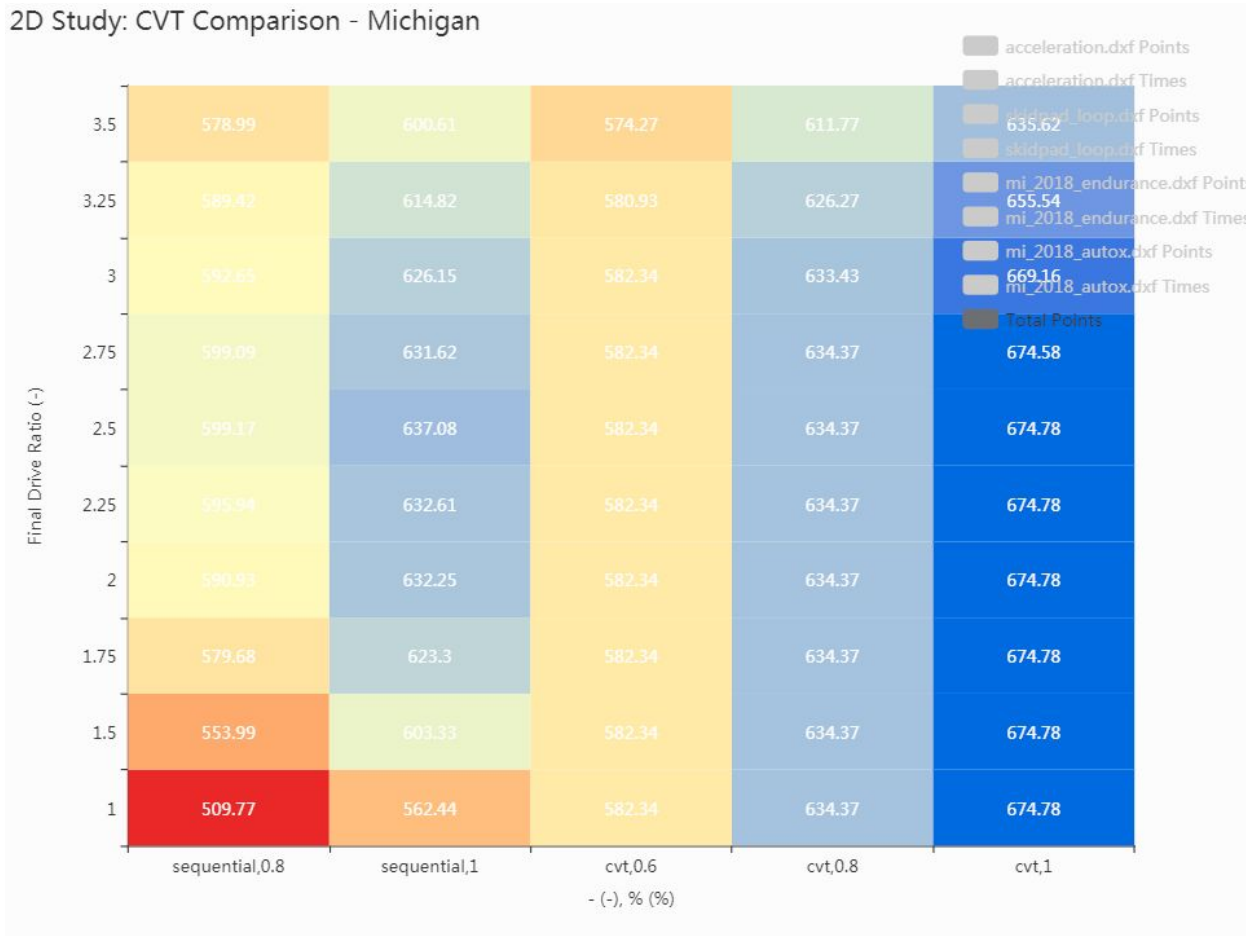
Max: 554 (in 3 gears), next max: 541 (in 1 gear), min: -6

There are small gains in points to be had in switching to a 3 gear spread. The bigger benefit may be in drivability, but issues may arise in lugging the engine. The lowest RPM would drop from 7500 RPM to 4000 RPM (the peak being 9500 in either case)- and this is assuming ‘perfect’ shifts. If a driver shifts early, they would lug the engine even further.

14. CVTs

A CVT is, on simple paper, an excellent way to improve performance- the engine is kept always in the powerband. However, in reality, they suffer from efficiency losses. RoseLap models CVTs as picking a ratio that puts the engine in a position where it produces maximum power.





With perfect drivetrain efficiency, it's clear that the CVT wins out. But, when there is a 20% efficiency difference, the points scored is nearly the same. This, of course, still doesn't factor in that a CVT may not gear perfectly.