Laptime Simulation with RoseLap for RGP007

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1. Limitations and Objectives

Laptime simulation shows itself to be a potentially powerful tool for driving the development direction of a Formula SAE car. The extent to which it can be used is highly dependent upon the model used and parameters included. RoseLap (as of version 3) models the following:

- Weight transfer: ‘two-tire’ model which considers longitudinal weight transfer, but not lateral.
- Tires: Tires have a constant coefficient of friction and are modeled as grip circles.
- Engine: steady-state torque curve that is linearly interpolated. Fuel efficiency is computed based on work done by the engine.
- Transmission: multiple gear ratios, while selecting the one which maximises output torque. A variable shift time (where 0 power is output) is modeled.
- Aerodynamics: drag and downforce that obey a square relationship with velocity.
- Brakes: constant brake biasing and dynamic (optimal) brake biasing are both modeled. Assumes impending slip.
- Driver: driver is ‘perfect’; always strives to hit the highest speed and brake as deeply as possible.

RoseLap also allows for points simulation; that is, computing expected point values from competing in the dynamic events.

Each subsystem has different things they would like to learn from such simulation. Many of these are not modeled because of the physics simplifications assumed. The desired details to learn are:

All systems:
- What is the benefit of removing every 1 pound of dead weight from the car?

Aerodynamics:
- At what cost of weight and drag can downforce come at to pay off?
- (potentially answerable with some modification to v3) Can wings that are designed for yaw offer substantial improvement?
- (not answerable with v3) Can wings be designed that exert a moment so as to counteract lateral weight transfer?

Brakes:
- What is the benefit of adjustable brake biasing?
- What range of brake biasing is ideal?

Chassis:
- (answer may not be valid with v3) What CG position should we target?
- (not answerable with v3) What amount of chassis stiffness is desirable?

Drivetrain:
- What gear ratio is best? Does this value change from course-to-course or competition-to-competition?
- What is the benefit of reducing shifting time by every 10ms?
- (not answerable with v3) What differential (or event spool) setup should be used?

Engine:
- What engine configuration should we shoot for?
    - Is a turbocharger worth it?
    - Is the YFZ450R the correct engine to continue with?

    - What other options out there should we be looking at?

Suspension/Unsprung:

- (meaning of answer questionable) What is the benefit of increasing tire coefficient of friction?
- (not answerable with v3) What spring stiffnesses/motion ratios should be used?
- (not answerable with v3) What ARB stiffness (if any) should be used?
- (not answerable with v3) What effect does unsprung mass reduction have on the car?
- (not answerable with v3) What damping rates should be used?

While many of these questions may remain unanswered with v3 and will wait for v4 or even v5 to be answered, the ones that can will be answered here.

This document will discuss the many experiments conducted, along with developmental changes to the model if there are any, as we go along.

2. *Mesh Convergence*

By: Thaddeus Hughes
Date: June 2017

Our laptime simulation is a finite method, meaning that the size of mesh used on a track affects performance. To ensure results are useful, we must perform 'mesh convergence'- checking how the mesh affects outcomes. We can afford to be lenient since the goal of laptime simulation is to provide trends, not to predict outcomes. There are three different track types in terms of layout: acceleration, skid pad, and autocross. We will examine all three.

Figure 2.1: Acceleration Mesh Convergence

Figure 2.2: Autocross mesh convergence

Figure 2.3: Skidpad mesh convergence

Note that the results should converge as mesh size goes to the left. While this isn't true, we can still pick a point close to where the benefits taper off that balances convergence and computational performance. For acceleration and skidpad,a good compromise seems to be 0.2 ft, and for autocross, around 0.3 to 0.5 ft.

3. Correlation - Aero vs. Non-aero cornering

By: Thaddeus Hughes
Date: 7/5/2017

The aerodynamics team conducted a study to evaluate the aerodynamics package on RGP005. This was done by placing an accelerometer on RGP005, then taking a corner of defined radius as fast as possible, with multiple attempts. The results are shown below in Figure 2.1.

Figure 3.1: Lateral Acceleration Results from Physical Aero Testing

By simulating RGP005 with a varying coefficient of friction, we can find the COF that best matches these results for each test by looking at the lateral acceleration during the steady-state portion of a turn. This coefficient will capture suspension characteristics during a roll- where the tire COF matters the most.

Figure 3.2: Simulations without aero package

Figure 3.3: Simulations with aero package

Downforce (lbf)	Aero Bias	Track Radius (m)	Lateral Acceleration (Testing)	Best COF for Simulation	Averages
61	70%	11.5	1.579	1.506	
		15.9	1.648	1.535	
		20.3	1.576	1.444	1.50
0	70%	11.5	1.394	1.428	
		15.9	1.332	1.373	
		20.3	1.354	1.396	1.40
61	60%	11.5	1.579	1.5	
		15.9	1.648	1.528	
		20.3	1.576	1.425	1.48

Figure 3.4: Lateral Acceleration Results from Laptime Simulation

CFD predicted a CP somewhere between 60% and 70% depending on conditions around the drivers' head. We can see that the effective tire coefficient is somewhere around 1.50- this will be useful in simulation provided suspension characteristics do not change radically.

4. Study - Brake Bias

By: Thaddeus Hughes
Date: 7/10/2017

To begin setting up the car with a two-tire model, the brake bias parameter must be set. This also allows us to determine what range of biasing values to allow for in testing, and gague benefit (if any) automatic or adjustable on-the-fly biasing would provide. Brakes are only used in the autocross and endurance events; these have been studied below.

Figure 4.1: Points for each dynamic event and point totals

Figure 4.2: Lap times for each dynamic event

Figure 4.3: Overall points in detail

Providing perfect biasing (both tires use all remaining grip) provides marginal improvement. At each competition, a 0.5 point improvement is seen by automatic biasing as opposed to a properly tuned bias value. This minute benefit is made even more small when we remember that this requires perfect biasing in every braking event- the driver must adjust bias perfectly. This is a lot of training- so adjusting biasing on the fly is not a priority for our team.

5. Study - Shift Time

By: Thaddeus Hughes
Date: 7/10/2017

Increased shift time means more time where the engine is not laying down power- thus, increased laptime. It's obvious that decreasing this time will be beneficial without any downsides in itself, but we would like to determine how much of our development and weight should be pushed towards reducing this parameter.

Figure 5.1: Laptimes

In all events, the relationship is roughly linear.

Figure 5.2: Points

Event	Time - 0ms	Time - 200ms	Time Improvement	% Improvement
Acceleration	4.41	4.71	0.30	6.63%
Autocross-MI2017	54.00	55.50	1.50	2.74%
Endurance-MI2017	73.45	73.50	0.05	0.07%
Autocross-NE2015	59.85	60.85	1.00	1.66%
Endurance-NE2017	85.45	86.93	1.48	1.72%

Figure 5.3: Laptime improvements, tabulated

Event	Points - 0ms	Points- 200ms	Point Improvement	Points per 10ms improvement
Acceleration	80.0	63.0	17.0	0.85
Autocross-MI2017	35.0	27.0	8.0	0.40
Endurance-MI2017	292.0	269.5	22.5	1.13
Michigan Overall	450.5	403.3	47.2	2.36
Autocross-NE2015	110.0	104.0	6.0	0.30
Endurance-NE2017	270.8	257.1	13.7	0.68
Lincoln Overall	504.1	467.5	36.6	1.83

Figure 5.4: Point improvements, tabulated

This is a fairly important parameter, as reduction in shifting times by a significant amount can have moderate impact on points at competition; around 2 points for every 10ms removed from shifting time. Dialing in the shifter will definitely be a job for the team this year.

6. Study - Dead Weight

By: Thaddeus Hughes
Date: 7/10/2017

Minimizing weight is seen as the Holy Grail of FSAE. How big of a deal is it, really? In this study, we will add and subtract bricks from the CG of RGP006.

Figure 5.1: Totalled points

Figure 6.2: Points of each event

Figure 6.3: Detail of lap times at each event (skidpad and accel are the same for each competition)

Event	Time - 400 lb	Time - 700 lb	Time Improvement	% Improvement
Skidpad	4.8	4.874	0.07	1.53%
Acceleration	4.53	5.00	0.47	9.86%
Autocross-MI2017	54.55	56.55	2.00	3.60%
Endurance-MI2017	74.25	77.00	2.75	3.64%
Autocross-NE2015	85.00	88.50	3.50	4.03%
Endurance-NE2017	59.60	61.90	2.30	3.79%

Figure 6.4: Lap time improvement by weight

Event	Points - 400 lb	Points - 700 lb	Point Improvement	Points per 10lb lost
Skidpad	74.5	71.0	3.5	0.12
Acceleration	72.3	48.0	24.3	0.81
Autocross-MI2017	32.0	21.8	10.2	0.34
Endurance-MI2017	283.0	253.0	30.0	1.00
Michigan Overall	461.2	394.6	66.6	2.22
Autocross-NE2015	111.5	98.0	13.5	0.45
Endurance-NE2017	276.0	243.0	33.0	1.10
Lincoln Overall	534.0	460.0	74.0	3.70

Figure 6.5: Point improvement by weight

Overall, these results seem pretty… underwhelming. Part of this is because of the tire model used- ideally, tires perform better at lighter loads and so a lighter car will have a higher effective coefficient of friction. Our car only performs better in the corners because aerodynamic effects are diminished by added weight. Including tire models would create a more accurate assessment of how weight affects performance.

Results for acceleration are surprising at first- shouldn't halving mass halve time? Not quite- it actually (in an ideal F=ma world) should vary with the root of mass. So, a ~32% increase in time. Even so, we only see an 11% increase. A bit strange. Part of this may be due to the launch period, which is tire limited, and so each vehicle behaves roughly the same to begin with.

Figure 6.7: Maple calculations to understand the effect of mass and force on acceleration event time

Looking at a light and heavy car run side by side, we see that both velocity profiles look similar for the first ~30 feet.

Figure 6.7: Detail of acceleration drags between a light and heavy car

Ultimately, this study is sobering to weight reduction efforts- weight reduction on the order of 10 pounds may very well be unimportant when it comes at the cost of reduced drive time, reliability, or power or downforce.

7. *Study - Final Drive Ratio and Turbocharger*

By: Thaddeus Hughes
Date: 7/12/2017

Picking the best final drive ratio can be a bit of educated guesswork. Too tall, and your maximum speed is hampered. Too short, and your acceleration is diminished. Shifting time can further complicate the issue- are gears covering useful speeds? We will examine the effect of final drive ratio on a turbocharged and naturally aspirated RGP006 with preliminary torque curves shown in Figure 7.1.

RoseGPE lacks the development time to do much more than use a YFZ450R in RGP007, with a turbocharger or without. Laptime simulation allows us, though, to examine the benefit added by the turbocharger to assess its worth on the car. We can also examine other engines on the market to develop for use on RGP008.

The following torque curves for the YFZ450R were created with GT suite. These two configurations will be tested side-by-side. Because of the first low-end peak in the naturally aspirated curve, the shifting algorithm breaks. By cutting off this bit of the curve, 21.2 ft*lbf will be used in place whenever calculating torque below 4500 RPM. This should make the naturally aspirated curve seem less desirable, but only during launch- in normal operating condition, the engine sits over 6000 RPM, typically.

	YFZ450R - Naturally Aspirated			YFZ450R - Turbocharged	
RPM	Nm	ft*lbf	RPM	Nm	ft*lbf
1500	41.9	30.9	1500	34.1	25.2
2500	45.7	33.7	2000	35.3	26.0
3500	45.8	33.8	2500	35.4	26.1
4500	45.0	33.2	3000	36.2	26.7
5500	44.1	32.5	3500	38.5	28.4
6500	41.0	30.2	4000	37.3	27.5
7500	40.8	30.1	4500	48.6	35.8
8500	42.2	31.1	5000	50.8	37.5
9500	39.2	28.9	5500	52.7	38.9
			6000	55.0	40.6
			6500	59.6	44.0
			7000	59.5	43.9
			7500	55.3	40.8
			8000	52.8	38.9
			8500	53.1	39.2
			9000	51.2	37.8
			9500	47.4	35.0

Figure 7.1: Curves used in this analysis. Turbocharger also adds an extra 20 lbm to the car.

Figure 7.2: Overall points for both configurations versus final drive ratio at both competitions.

The turbocharger can be seen to add around 10 points of value at Lincoln and 17 at Michigan. If executed reliably, the turbo could definitely add value.

The best ratios for Lincoln and Michigan actually do overlap in the range of noise. Thus, a single sprocket can be picked for both competitions with no noticeable penalty- plus, the driver will not have to become reaccustomed to how the powertrain responds. But why do these point curves look the way they do? Let’s look at the relevant dynamic events.

Figure 7.3: Acceleration performance

For both the turbo and naturally aspirated, there exists a best gear ratio that isn't at an extreme- balancing launch with top speed. These peaks are actually rather close for both setups.

Figure 7.4: Autocross and Endurance performance

The autocross-like courses, however, tell a different story that shorter is better, seemingly without end. In an ideal world, then, we would use the optimized gear ratio for the acceleration event and then switch to the shortest final drive available for the remaining events. The only problem with this strategy is launch, which is inadequately modeled, and would be severely impaired by a taller ratio. This would require being very delicate on the clutch. In endurance this may not be that bad, but in autocross, launch very much matters.

8. Study - Aerodynamic Effects

By: Thaddeus Hughes
Date: 7/11/2017

Adding wings to the car means weight. What is the cost? Well, we can find out with a 3D study.

Figure 8.1: Overall points, Downforce vs. Mass

Figure 8.2: Acceleration and Mass Lap Times

Figure 8.3: Autocross and Endurance Lap Times

From Figure 8.1 we can determine the break-even and even profit rates for aerodynamics.

	Downforce	Weight	Downforce	Weight	Points	Downforce/Weight Break-Even	Average	Average
Lincoln 2015	58	535	84	595	493	0.424	0.415	0.637
	75	535	90	571	515	0.421		
	41	535	65	595	471	0.400		
Michigan 2017	71	535	90	556	426	0.922	0.859	
	55	535	90	577	413	0.843		
	38	535	87	595	400	0.810		

Figure 8.4: Autocross and Endurance Points at multiple contours for each competition, costed

We will now examine drag and downforce.

Figure 8.5: Overall points, Downforce vs. Drag

Figure 8.6: Lap times for skidpad and acceleration events

Figure 8.7: Lap times for autocross and endurance courses

	Downforce	Drag	Downforce	Drag	Points	Downforce/Drag Break-Even	Average	Average
Lincoln 2015	82	0	90	25	528	0.339	0.409	0.621
	65	0	84	45	512	0.430		
	47	0	67	45	496	0.435		
	30	0	49	45	480	0.433		
Michigan 2017	77	0	90	17	444	0.785	0.833	
	59	0	90	38	432	0.816		
	36	0	79	45	424	0.953		
	20	0	55	45	416	0.778		

The results show that Lincoln allows for a much less efficient wing design. This makes sense, as Michigan's courses are much straighter and so drag more negatively impacts performance.

9. *Study - CG Position*

By: Thaddeus Hughes
Date: 7/11/2017

RoseLap v3's two-tire model allows us to study the effects of CG position to some degree. This is limited in that only longitudinal load transfer is taken into account. The effect of lateral transfer are neglected. Thus, the significance of these results should be questioned.

Figure 9.1: Acceleration and Skidpad Times

Figure 9.2: Michigan 2017 Lap Times

Figure 9.3: Lincoln 2015 Lap Times

Figure 9.4: Competition points overall

An interesting trend occurs throughout all studies (except for skid pad): there is a diagonal band where best performance is achieved. A lower CG should be followed up by more rear biasing. Why, though? Well, it’s because it’s all about forward longitudinal acceleration. The rear tires need to have adequate traction such that the engine becomes the limiting factor in order to maximise power output. The constant coefficient of friction and simplified physics means that we pay no traction penalty for shifting weight where it is desired the most. To accurately study the effects, more accurate tire models are definitely due.

10. Study - Tire Coefficient of Friction

By: Thaddeus Hughes
Date: 7/11/2017

Figure 10.1: Event times as a function of coefficient of friction

Figure 10.2: Competition points as a function of coefficient of friction

The obvious conclusion that was known before even envisioning the simulation holds true: increasing grip is the altar at which racing bows to. Doubling friction more than doubles points. In nearly all cases, a slightly curved relationship (although mostly linear) holds- the only exception being the acceleration event, where once tire grip exceeds a certain point, the engine becomes the limiting factor.

	Time at COF =			% Improvement / COF	
Event	**1.0**	**1.6**	**2.2**	**1.0 -> 1.6**	**1.6 -> 2.2**
Skidpad	5.97	4.69	3.97	40.03%	27.71%
Acceleration	5.32	4.67	4.65	21.69%	0.72%
Autocross-MI2017	66.50	54.00	48.3	34.58%	18.57%
Endurance-MI2017	90.00	73.50	66	33.64%	17.92%
Autocross-NE2015	73.88	59.27	51.5	36.58%	23.38%
Endurance-NE2015	105.50	84.50	73.6	36.84%	22.98%

Figure 10.3: Lap times at turnpoints and improvements in these ranges

	Points at COF =			Improvement / 0.1 COF	
Event	**1.0**	**1.6**	**2.2**	**1.0 -> 1.6**	**1.6 -> 2.2**
Skidpad	26.6	81.7	137.5	9.18	9.30
Acceleration	34.0	65.2	66.4	5.20	0.20
Autocross-MI2017	-20.0	35.0	69	9.17	5.67
Endurance-MI2017	140.0	289.5	387	24.92	16.25
Michigan Overall	179.0	473.0	658.8	49.00	30.97
Autocross-NE2015	40.0	114.0	168.5	12.33	9.08
Endurance-NE2015	121.8	280.5	400	26.45	19.92
Lincoln Overall	221.2	541.0	772	53.30	38.50

Figure 10.4: Points at turnpoints and improvements in these ranges

This shows that efforts to improve the coefficient of friction in increments as small as 0.1 will have quite drastic payoff, although the benefit diminishes slightly as coefficient of friction continues to increase.

11. Study - Turbocharger Effects on Aerodynamic effects

By: Thaddeus Hughes
Date: 7/16/2017

The Aerodynamic Effects study is repeated for the configuration of RGP007 with a turbo and without as described in Study - Final Drive Ratio and Turbocharger. The points for both Lincoln and Michigan are combined in the next plots.

Seeing that the contour lines are steeper in the turbocharged curve, it becomes clear that downforce can be added with more drag to break even with a turbocharger- meaning that adding a turbo opens up the door for more aerodynamic development.

12. Mid-Summer Conclusions and Recommendations

By: Thaddeus Hughes
Date: 7/17/2017

Shifting Time: Every reduction of shift time by 10ms can improve points by 1.8-2.4 per competition.

Dead Weight: Simplistic tire models suggest that every 10lb of dead sprung weight lost equates to a gain of 2.2-3.7 points per competition.

Final Drive Ratio: A single sprocket size exists that will perform well across both Lincoln and Michigan competitions. Changing sprocket size for the acceleration event could be beneficial.

Aerodynamic events: 1 pound of drag or weight can be added for every 0.4 to 0.9 pounds of downforce to break even. Do better in order to improve.

CG position: No real conclusion.

Tire COF: Increasing effective COF by 0.1 can increase points by 30-53 per competition.

Turbocharger: Adding a turbocharger to the YFZ450R will allow for a moderate points improvement, and make downforce more profitable when it comes at the expense of drag.