RENSSELAER
MOTORSPORT

Lapsim Presentation

Erich Bahm, bahmerich@gmail.com

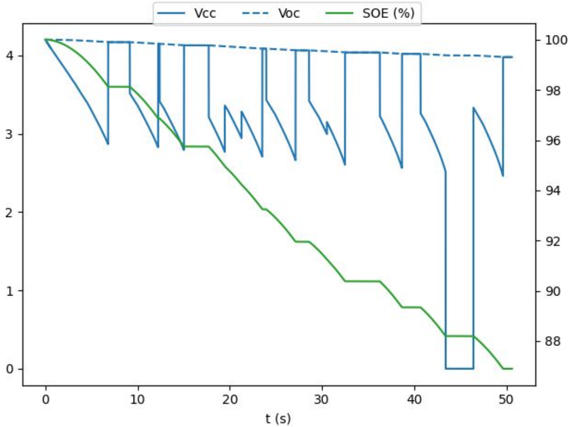
github.com/RensselaerMotorsport/LapSim

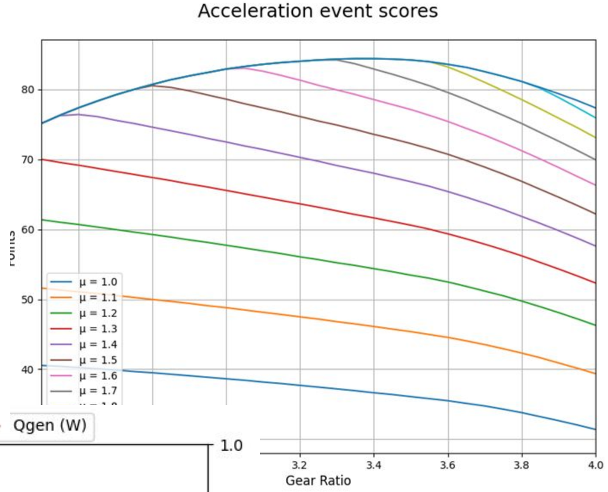
Agenda

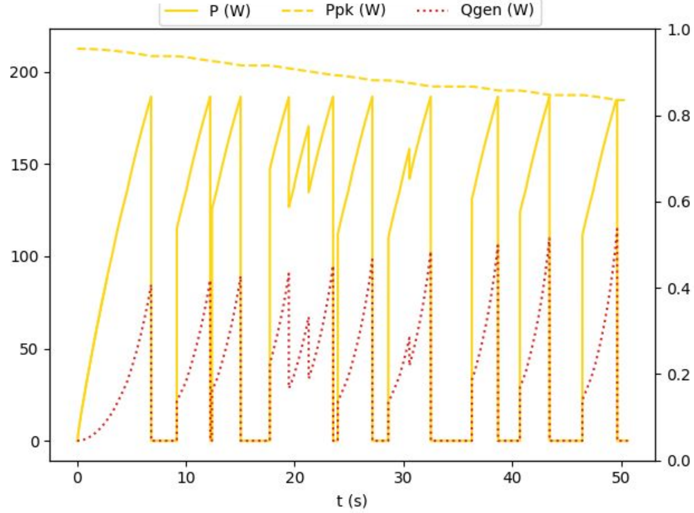
- What is Lapsim?
- System Architecture
- Track model
- Subsystem models
- Appendices
- Questions

What is Lapsim?

- In-house EV lap-time simulator for FSAE tracks used to compare high-level design decisions
- Built-in battery model
- Single track bicycle
  - Steady state load transfer
- Simplified traction (F=Nμ)
- 100mm track divisions
- Requires course accelerometer data

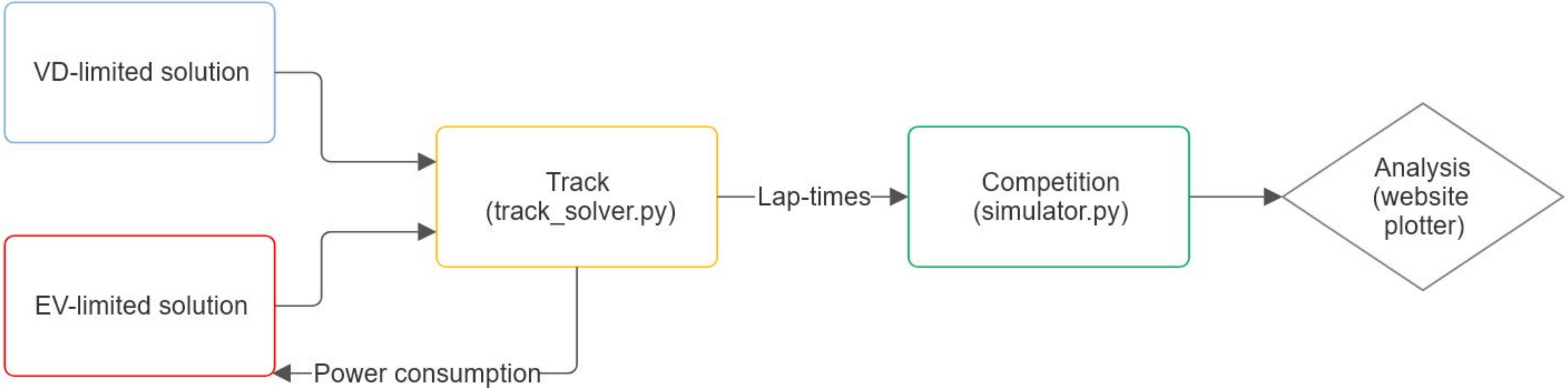






https://github.com/RensselaerMotorsport/LapSim

System architecture



VD-limited solution:

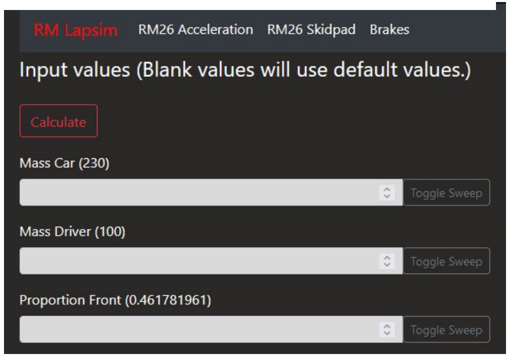
tires.py

aerodynamics.py

EV-limited solution:

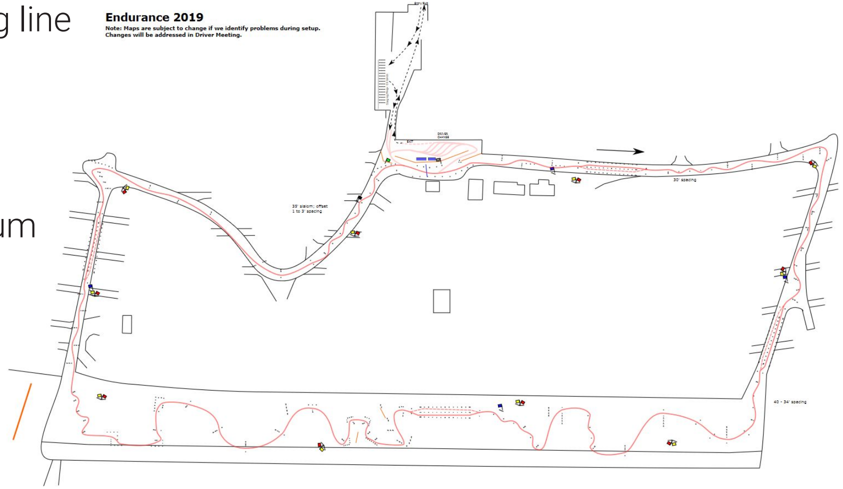
hvbattery.py

drivetrain.py



Track Definition

- Track is defined as a set of positions (x) and inverse cornering radii (ir)
  - Increments of 0.1m
- 1. The track is created using accelerometer and GPS data
  - The “ideal” racing line is the line that the driver takes
  - Lapsim doesn’t calculate a racing line
- 2. This track is split into regions separated by apexes (*list_apexes*)
  - These apexes define the maximum speed on the track at that point
- 3. The model integrates through accelerating and braking to find the fastest completion



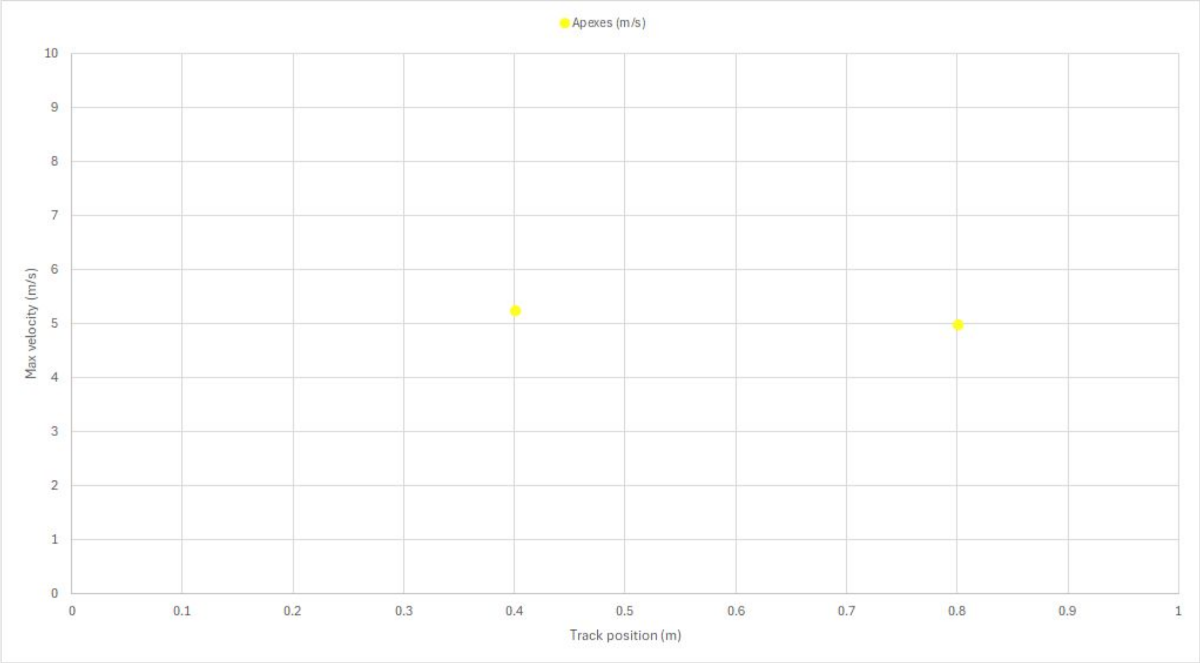
Track step 1 →

x (m)	ir (1/m)
0.1	0
0.2	0
0.3	0
0.4	0
0.5	0
0.6	0
0.7	0
0.8	0
0.9	0
1	-0.01723
1.1	-0.01688
1.2	-0.01655
1.3	-0.01622
1.4	-0.01591
1.5	-0.01561
1.6	-0.01532
1.7	-0.01499
1.8	-0.01468
1.9	-0.01438
2	-0.01409
2.1	-0.01381
2.2	-0.01355
2.3	-0.01329
2.4	-0.01304
2.5	-0.01379

Track Apexes

- At each position in the track, the maximum cornering speed is calculated

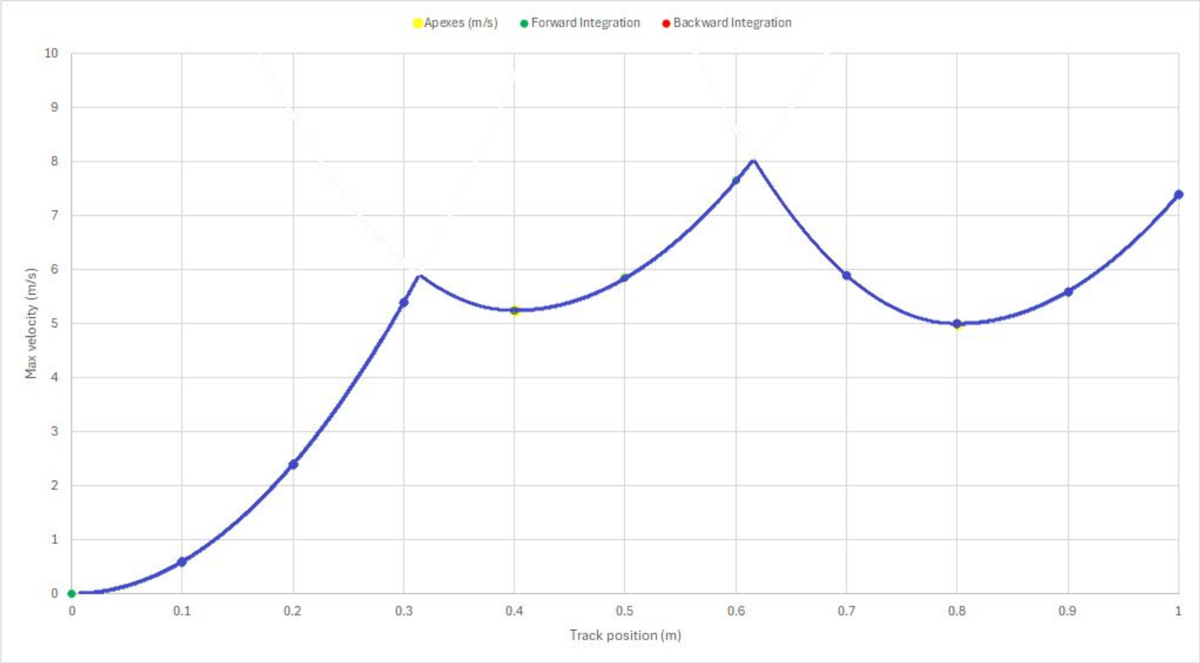
- The troughs (where max velocity is a minima) are the apexes



Track step 2

Track Apexes

- Forward integration accelerates the car with the peak available power (VD and EV limited)
- Backward integration decelerates the car with the peak available traction
- These two integration methods combined give result in the track output



Track step 3 (Animated)

Aerodynamics

- C_l and C_d values obtained through CFD, and experimentally
- Frontal area measured using CAD

- C_l: Coefficient of lift
- C_d: Coefficient of drag
- A: Car frontal area (m^2)
- ρ: Air density (kg/m^3)
- v: car longitudinal velocity (m/s)

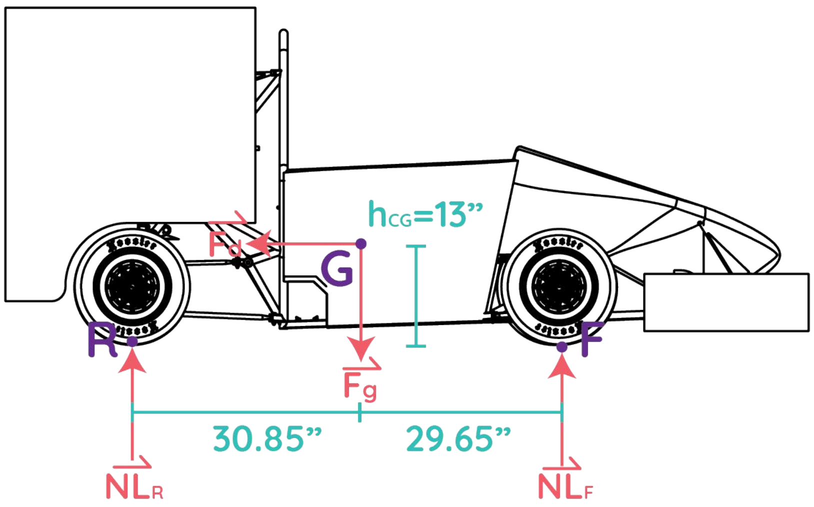
$$F_l = \frac{\rho A C_l v^2}{2}$$

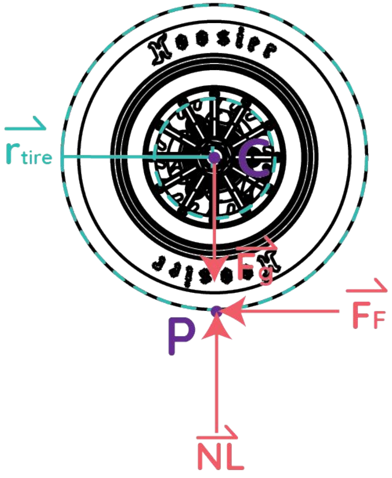
calc_down_force

$$F_d = \frac{\rho A C_d v^2}{2}$$

calc_drag_force

Suspension and Tires





Suspension and Tires

- μ_x and μ_y obtained from track testing
- CG position and wheelbase measured in CAD
- Idealized to a bicycle model (2 total tires)
- x: longitudinal, y: lateral

- F_z: Vertical load - front or rear (N)
- $\%_{fr}$: Front weight proportion
- h: CG height (m)
- L_w: Wheelbase (m)
- μ_x, μ_y: Coefficient of friction
- $F_{x,m}$, $F_{y,m}$: Max available traction (N)

$$F_{z,front} = \frac{\mu_x}{1 + \frac{h\mu_x}{L_w}} + F_l\%_{fr}$$

$$F_{z,rear} = \frac{\mu_x}{1 - \frac{h\mu_x}{L_w}} + F_l(1 - \%_{fr})$$

$$F_{x,m} = F_z\mu_x$$

calc_max_longitudinal force

$$F_{y,m} = F_z\mu_y$$

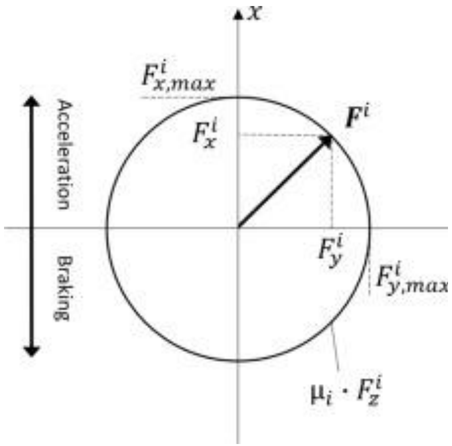
calc_max_lateral force

$$F_{rr} = F_z C_{rr}$$

calc_rolling_resistance

Suspension and Tires

- Traction ellipse around corners
- Longitudinal traction is reduced by lateral cornering load
- Apex speed is defined as the max speed in the pure lateral case



$$F_y = \frac{Mv^2}{r_c}$$

$$F_x = \sqrt{F_{x,m}^2 - \left(\frac{F_y F_{x,m}}{F_{y,m}}\right)^2}$$

- M: Total mass of car, driver, and battery (kg)
- g: Gravity (m/s^2)
- r_c: Corner radius (m)
- F_x, F_y: Applied longitudinal, lateral forces (N)
- v_{apex}: peak apex speed (m/s)

$$v_{apex} = \frac{M g \mu_y r_c}{M - F_l \mu_y}$$

calc_apex_speed

Accumulator

$$I = \frac{V_{oc}}{2R} - \sqrt{\frac{{V_{oc}}^2}{4R^2} - \frac{P}{R}} \qquad V_{cc} = \frac{P}{I} \qquad P_{pk} = V_{min}\frac{V_{oc} - V_{min}}{R} \qquad \Delta E = Pt \qquad Q_{gen} = I^2 R \qquad Q = Q_{gen}t \qquad \Delta T = \frac{Q}{mC_p}$$

Time	Electrical Power	Open Circuit Voltage	Impedance	Current	Closed Circuit Voltage	Peak Power Capability	Energy Consumption	Energy	SoE	Heat Generation	Heat Energy	Temp Rise	Temp
T	P	Voc	R	I	Vcc	W	dE	E	SoE	Qgen	Q	dT	T
[s]	[W]	[V]	[Ω]	[A]	[V]	[W]	[J]	[J]	[%]	[W]	[J]	[K]	[C]
0	0.000	4.200	0.015	0.000	4.200	283.333	0.000	58320	100.00	0.000	0.000	0.000	25.000
1	48.60	4.200	0.015	12.094	4.019	283.333	48.600	58271	99.92	2.194	2.194	0.035	25.035
2	48.60	4.199	0.015	12.098	4.017	283.097	48.600	58223	99.83	2.196	2.196	0.035	25.070
3	48.60	4.197	0.015	12.103	4.016	282.861	48.600	58174	99.75	2.197	2.197	0.035	25.105

$$I_{bm} = \min\left(I_{fuse}, I_{limit}\right) \qquad P_{bm} = \min\left(P_{bm}, P_{pk}\right)$$

$$P_{max} = R_{cell}\left(\left(\frac{V_{oc}}{2R_{cell}}\right)^2 - \left(\frac{V_{oc}}{2R_{cell}} - I_{bm}\right)^2\right)$$

calc_apex_speed

Accumulator

- Fuse limit and current limits defined by rules and selected fuse
- Cell resistance is not sensitive to temperature or current draw in current model

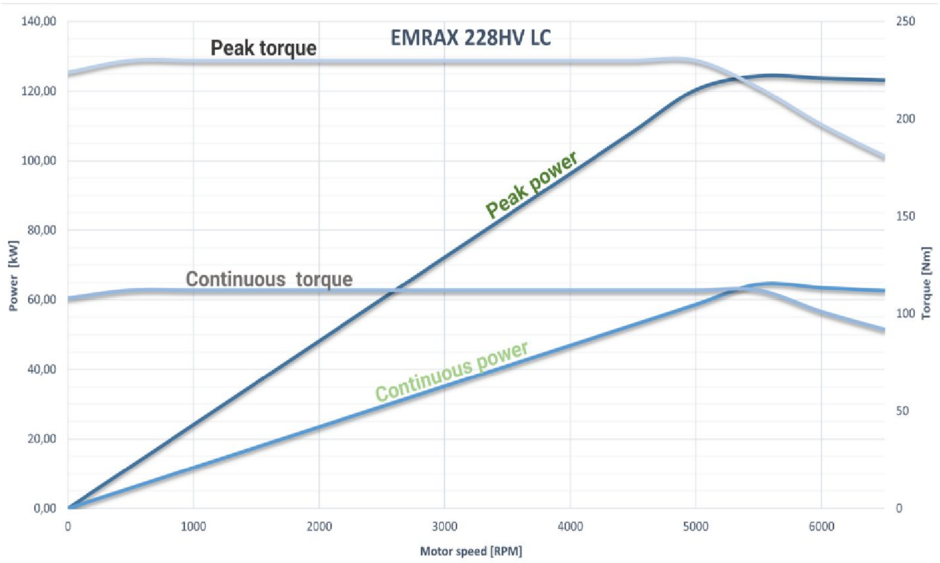
$$I_{bm} = \min\left(I_{fuse}, I_{limit}\right)$$

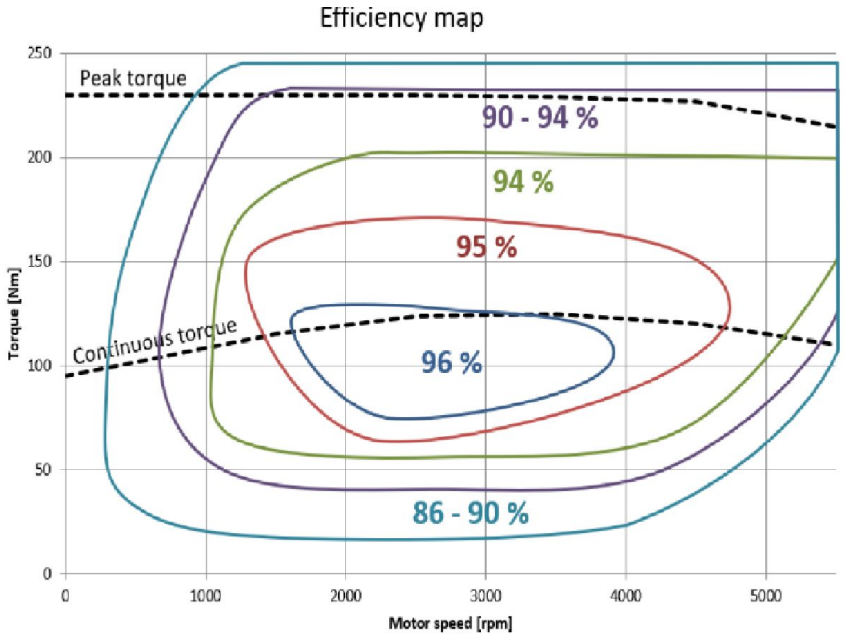
$$P_{bm} = R_{cell}\left(\left(\frac{V_{oc}}{2R_{cell}}\right)^2 - \left(\frac{V_{oc}}{2R_{cell}} - I_{bm}\right)^2\right)$$

calc_peak_power

- I_{bm}: Max battery output current (A)
- P_{bm}: Max cell power output (W)
- R_{cell}: Cell internal resistance (Ω)

Drivetrain


EMRAX 228HV LC
Peak torque
Continuous torque
Peak power
Continuous power
Power [kW]
Torque [Nm]
Motor speed [RPM]


Efficiency map
Peak torque
Continuous torque
90 - 94 %
94 %
95 %
96 %
86 - 90 %
Torque [Nm]
Motor speed [rpm]

Drivetrain

- Motor torque limit and efficiency defined by EMRAX manual
- HV efficiency is power loss across wires

- $T_{motor,m}$: Motor Torque limit (Nm)
- GR: Sprocket gear ratio
- F_W: Wheel force available (N)

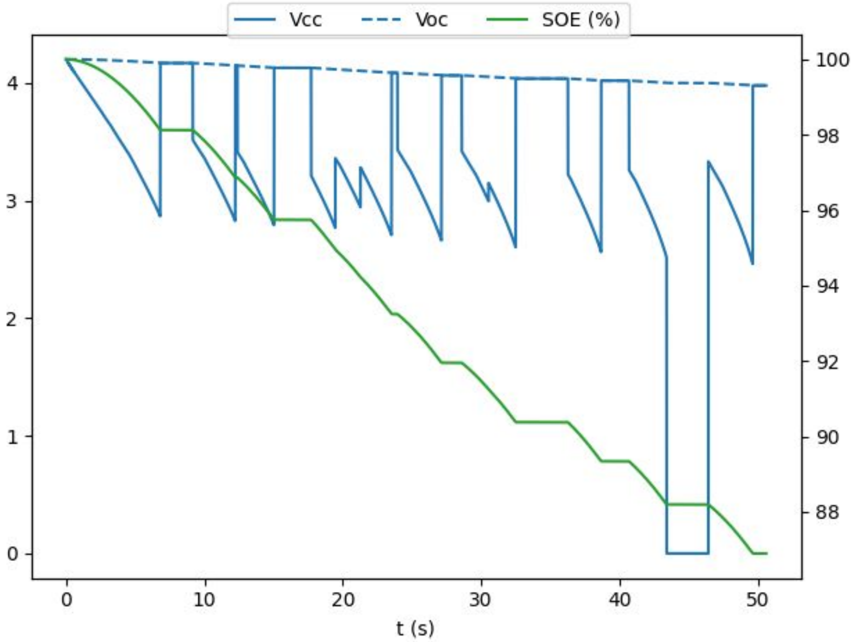
$$T_{bm} = \frac{30 P_{bm} \eta_{HV}}{RPM_M \pi}$$

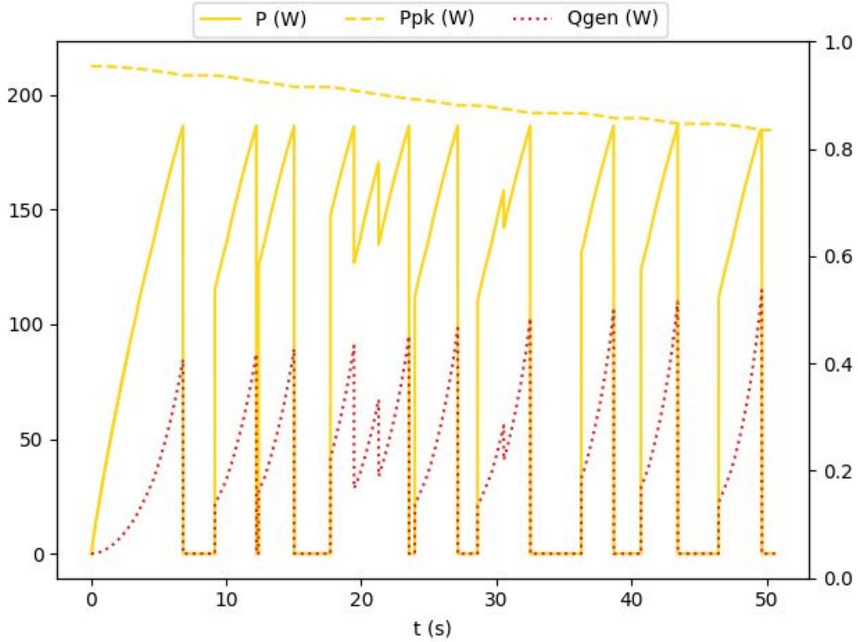
$$T_{motor,m} = \min\left(T_M, T_{bm}\right)$$

$$F_W = \frac{T_{motor,m} \eta_{DT} GR}{r_T}$$

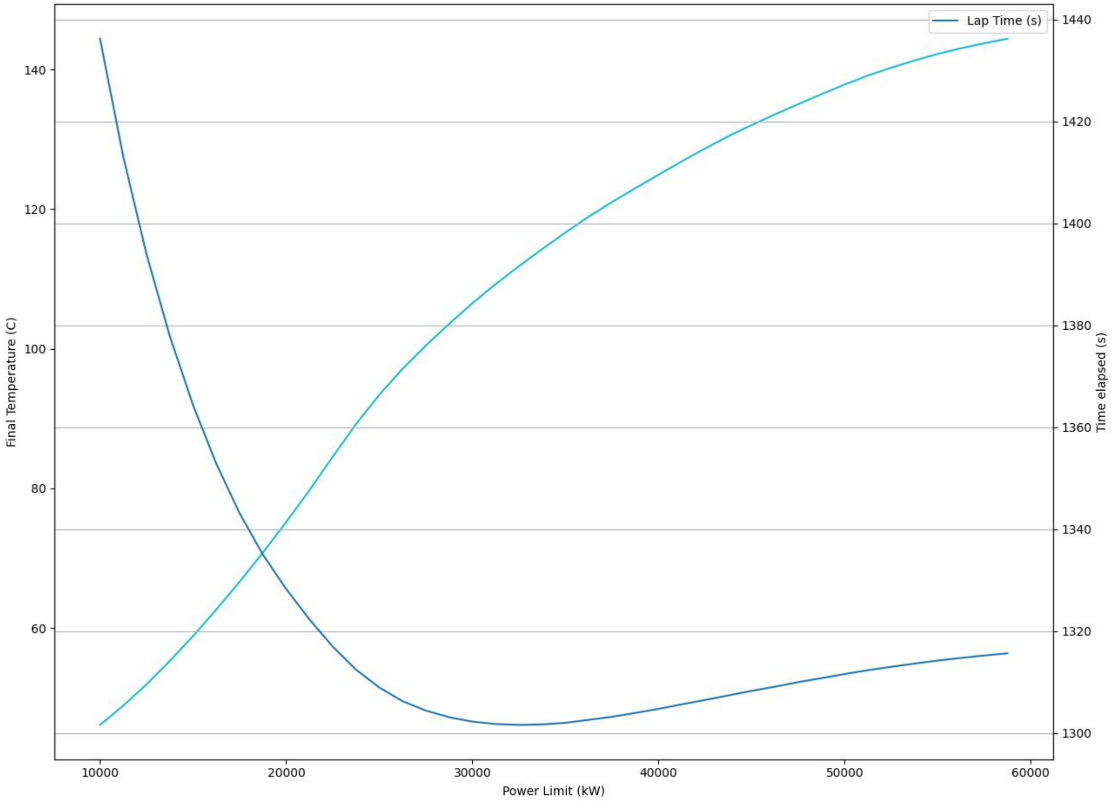
calc_wheel_force

Appendix 1 - Battery modelling

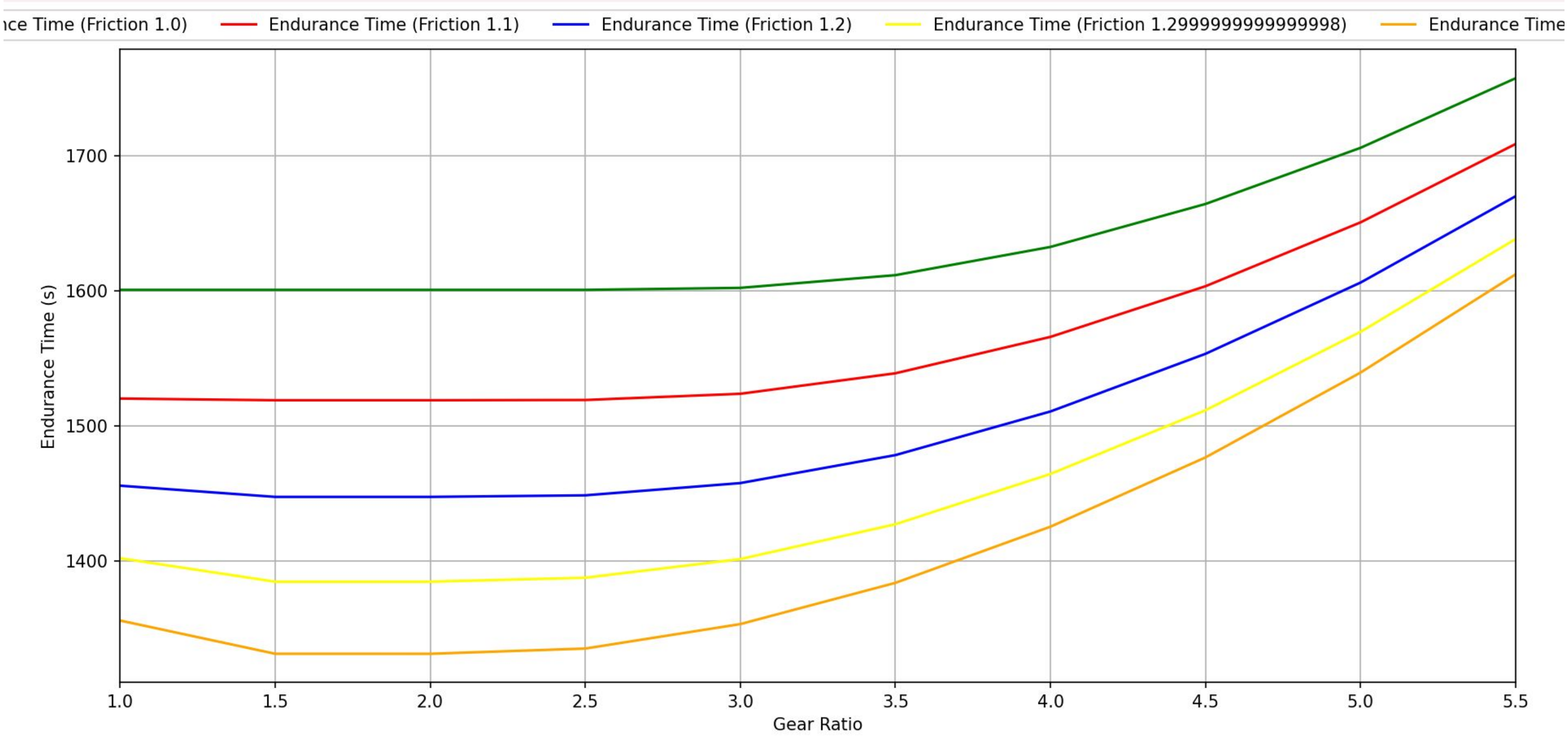




Appendix 2 - Power limiting



Appendix 3 - Gear ratio selection



Appendix 4 - Input list

Variable	Symbol	Units
mass_car	m_C	kg
mass_battery	m_B	kg
mass_driver	m_D	kg
wheelbase	L_W	m
CG_height	h	m
proportion_front	$\%_{fr}$	–
CoF	μ	–
rolling_resistance_coeff	Crr	–
tire_radius	r_t	m
rho	ρ	kg/m^3

Variable	Symbol	Units
Cd	C_d	–
Cl	C_l	–
A	A	m^2
fuse_current	I_{fuse}	A
cells_series	S	–
cells_parallel	P	–
cell_resistance	R_{cell}	Ω
cell_capacity	C_{cell}	Wh
cell_thermal_capacity	C_t	J/K
cell_mass	m_{cell}	kg

src\data\rm28.json

Appendix 4 - Input list

Variable	Symbol	Units
peak_torque	T_M	Nm
constant_kv	K_V	rpm/V_{DC}
constant_kt	K_T	Nm/A_{rms}
induced_voltage	ε	V_{rms}/RPM
gear_ratio	GR	–
tractive_efficiency	η_{HV}	–
drivetrain_efficiency	η_{DT}	–
power_limit	P_m	kW
current_limit	I_m	A

Questions

Competition