Strategy Optimization for the Bridgestone World Solar Challenge Using Dynamic Programming

Semester Project Presentation

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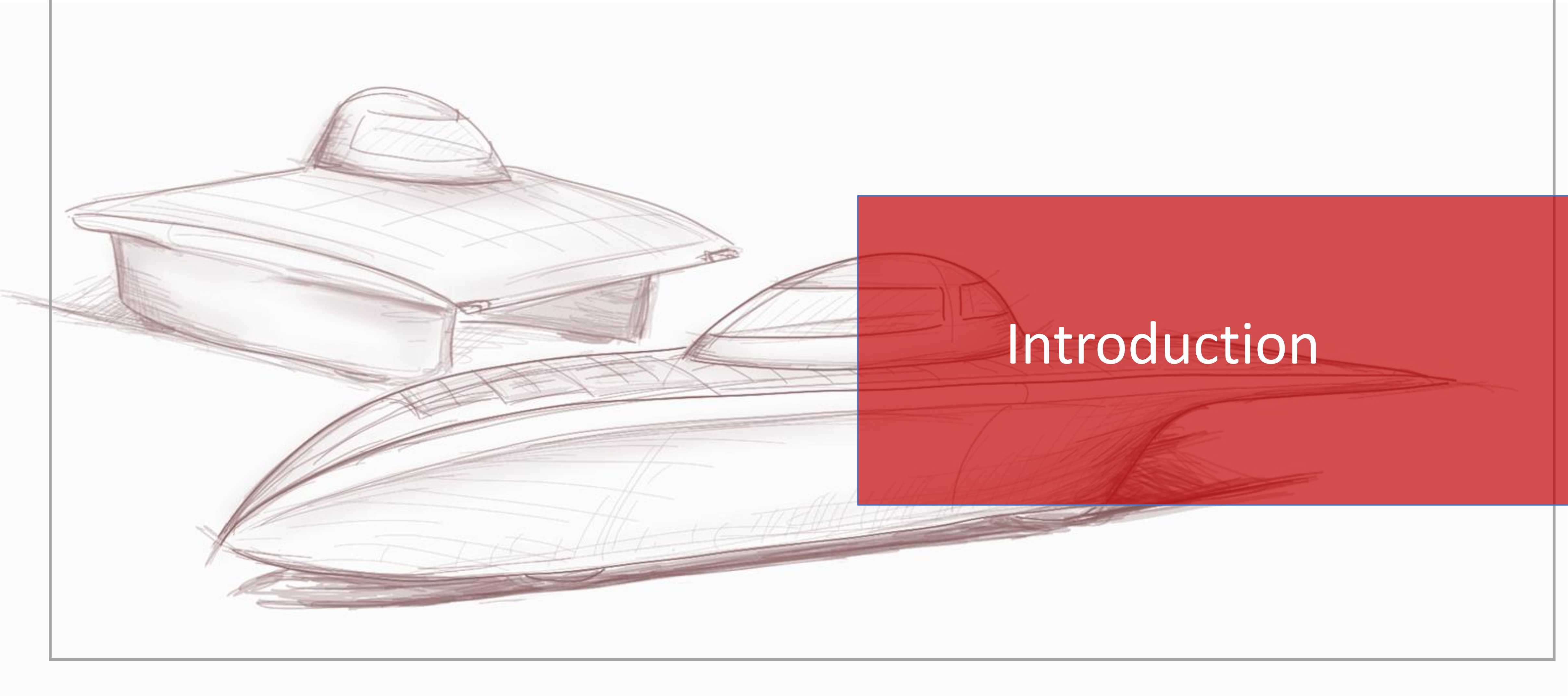
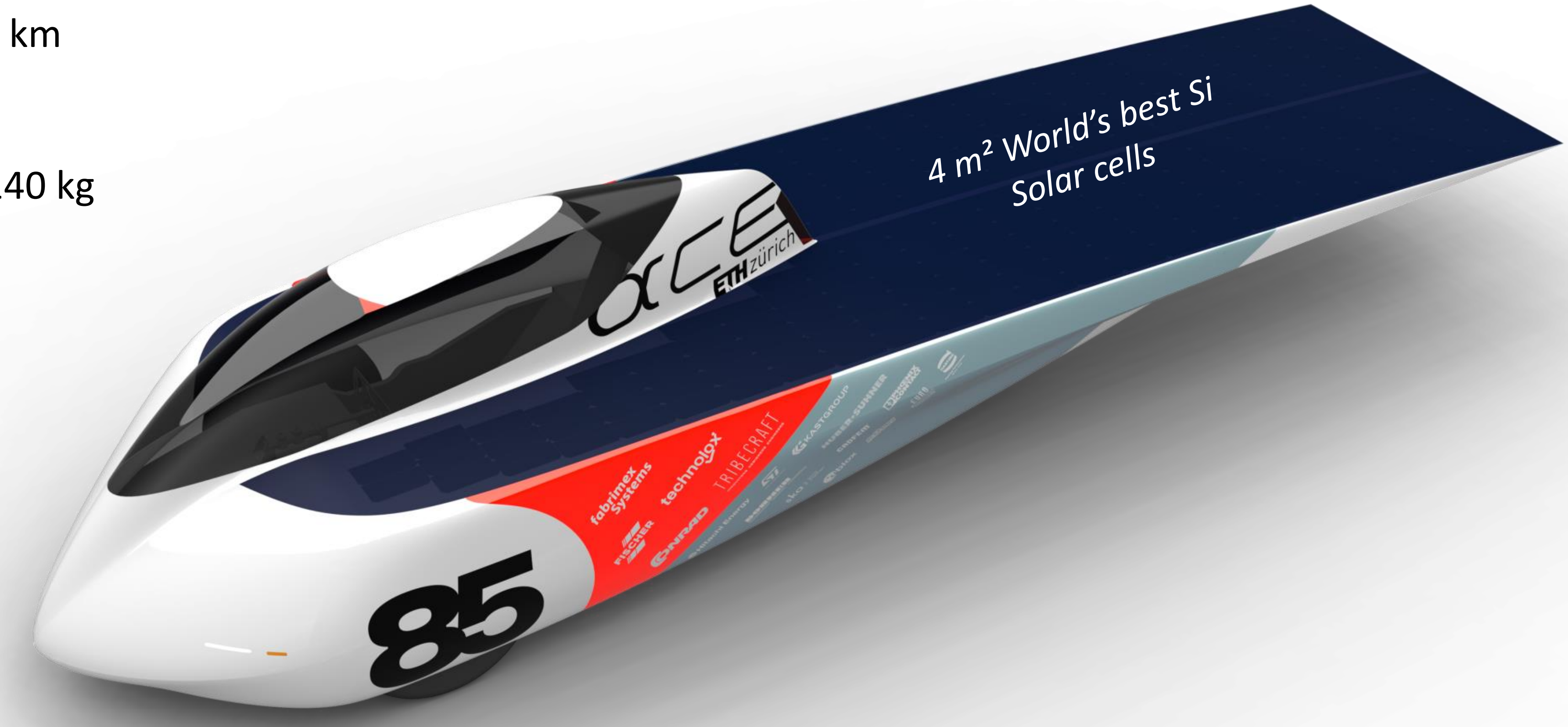
SOLAR RACING
IDSC
ETH zürich



Introduction

The Solar Race Car

Battery size: 5.2 kWh
Range in darkness: 500+ km
Top Speed: 155 km/h
0-100 km/h: 23 s
Weight without driver: 140 kg
Cd value: <0.09

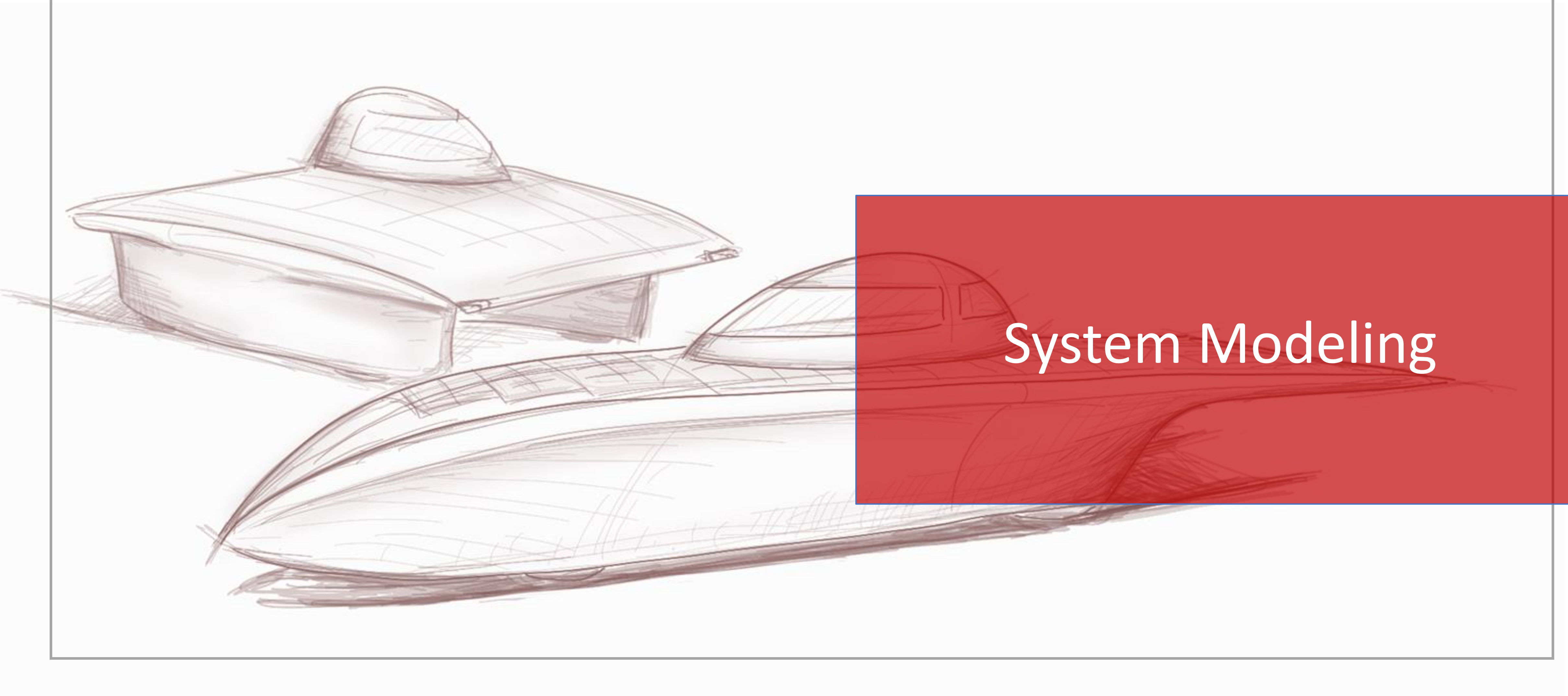


The Challenge

- Bridgestone World Solar Challenge 2023
- From Darwin to Adelaide, Australia
- Over 3000 km through the rough Outback
- 22nd-29th of October 2023
- 44 Teams from 21 countries
- 9 Control Stops: Wait for 30min (CS)
- Driving time: 8:00-17:00 each day
- 2-4 Night Stops (NS)
- Goal: Finish the race as fast as possible

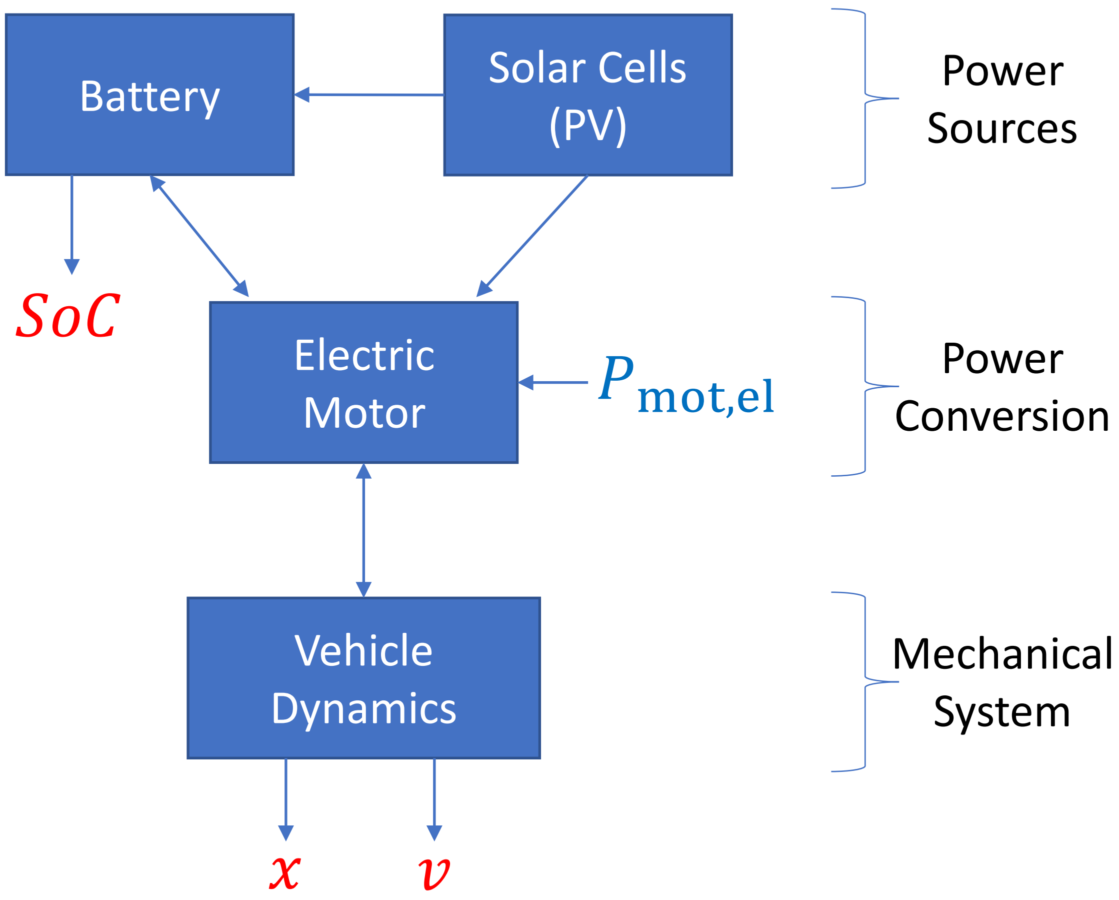
Agenda

1. System Modeling
2. Optimal Control Problem
3. Race Optimization Results
4. Case Studies
5. Conclusion and Outlook



System Modeling

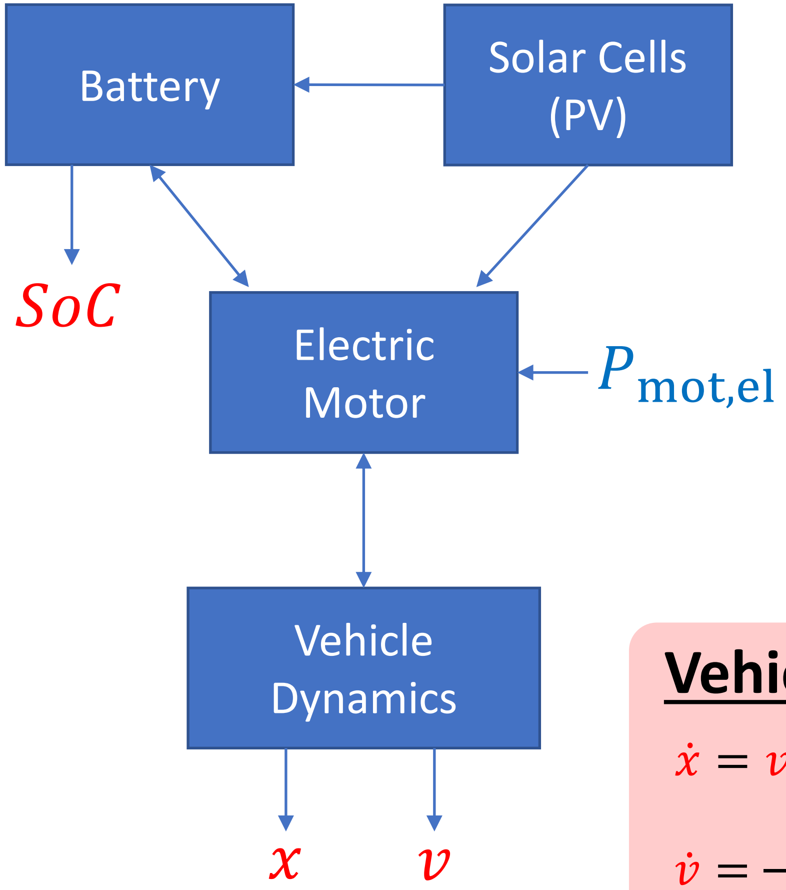
System Overview



States:
- State of Charge SoC
- Velocity v
- Position x

Input:
- Electric motor power $P_{\mathrm{mot,el}}$

State Dynamics



Battery Dynamics

$$\dot{SoC} = \frac{P_{\mathrm{PV}}(v, x, t) - P_{\mathrm{mot,el}}}{E_{\mathrm{bat,max}}}$$

PV Model

$$P_{\mathrm{PV}}(v, x, t) = A_{\mathrm{PV}} \cdot G(x, t) \cdot \eta_{\mathrm{PV}} \cdot \eta_{\mathrm{CF}}\,(v, x, t) \cdot \eta_{\mathrm{loss}}$$

Electric Motor Model

$$P_{\mathrm{mot,mec}}\left(P_{\mathrm{mot,el}}\right) = \begin{cases} e_{\mathrm{mot}} \cdot P_{\mathrm{mot,el}} - P_0 & , if\ P_{\mathrm{mot,el}} \geq P_0 \\ \dfrac{P_{\mathrm{mot,el}}}{e_{\mathrm{mot}}} - P_0 & , if\ P_{\mathrm{mot,el}} < P_0 \end{cases}$$

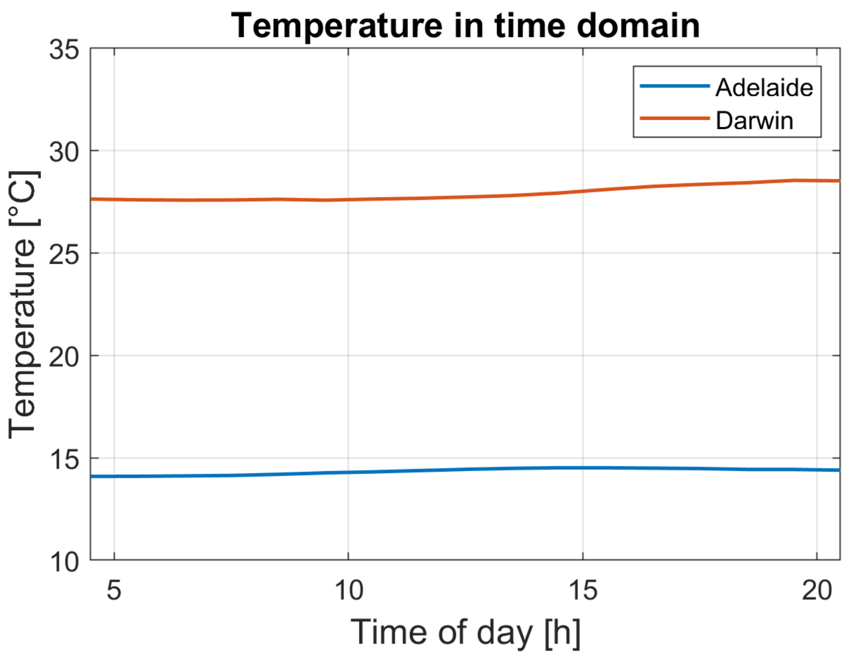
Vehicle Dynamics

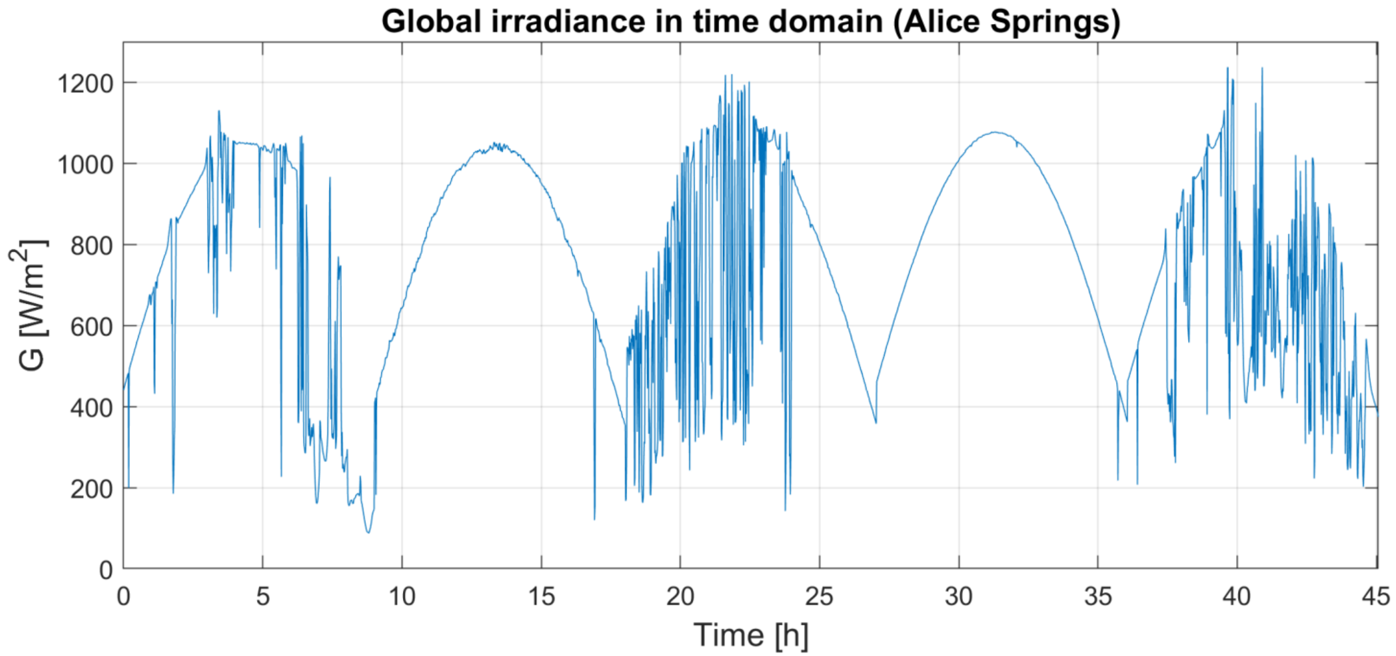
$$\dot{x} = v$$

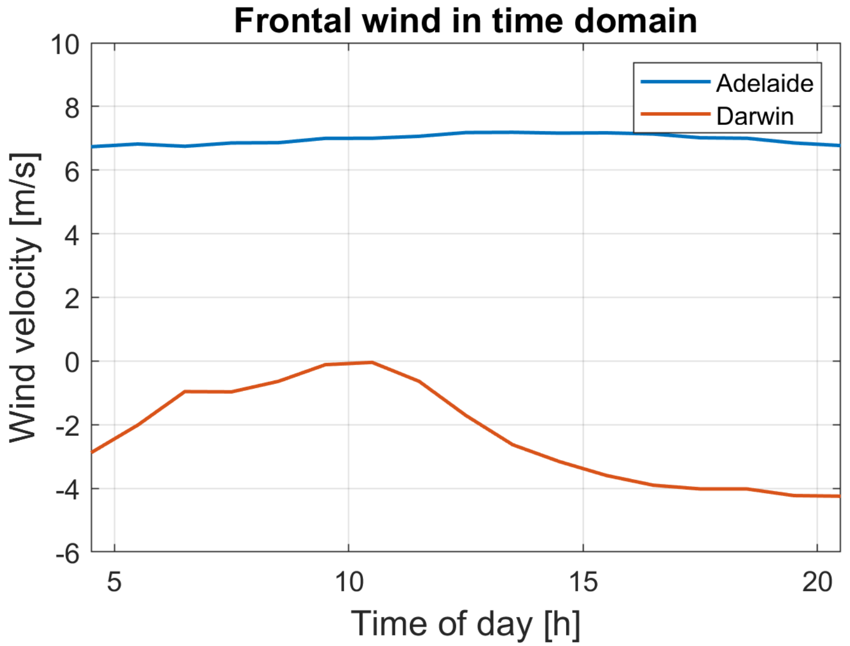
$$\dot{v} = \frac{1}{m \cdot v} \cdot \left(P_{\mathrm{mot,mec}}\left(P_{\mathrm{mot,el}}\right) - P_{\mathrm{aero}}(v, x, t) - P_{\mathrm{grade}}(v, x) - P_{\mathrm{roll}}(v, x) - P_{\mathrm{bear}}(v)\right)$$

External Input: Weather

1. Global irradiance: Relevant for PV power
2. Wind: Effect on drag and PV temperature
3. Temperature: Effect on PV temperature

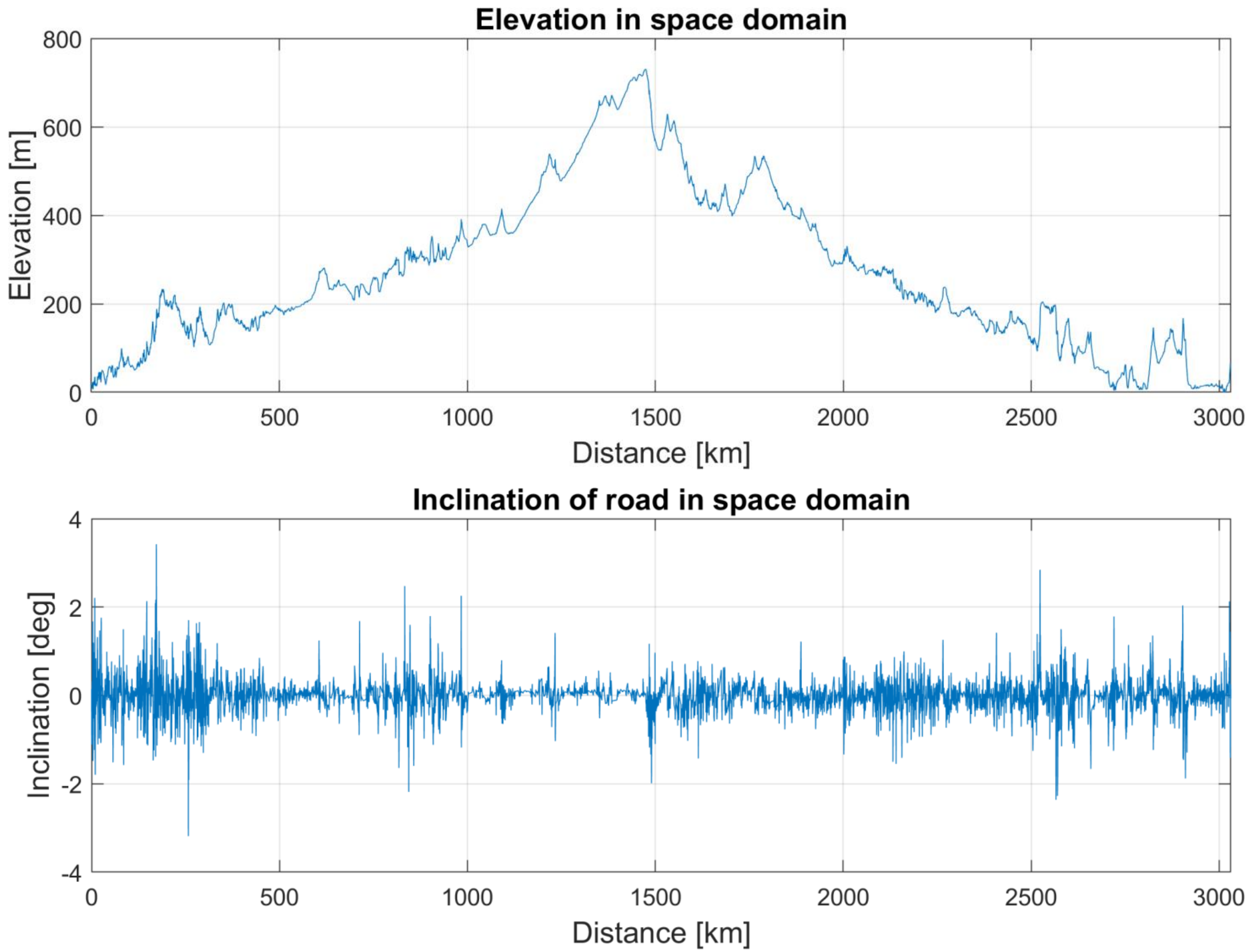






External Input: Route

1. Elevation: Effect on drag through air density
2. Road inclination: Effect on vehicle dynamics



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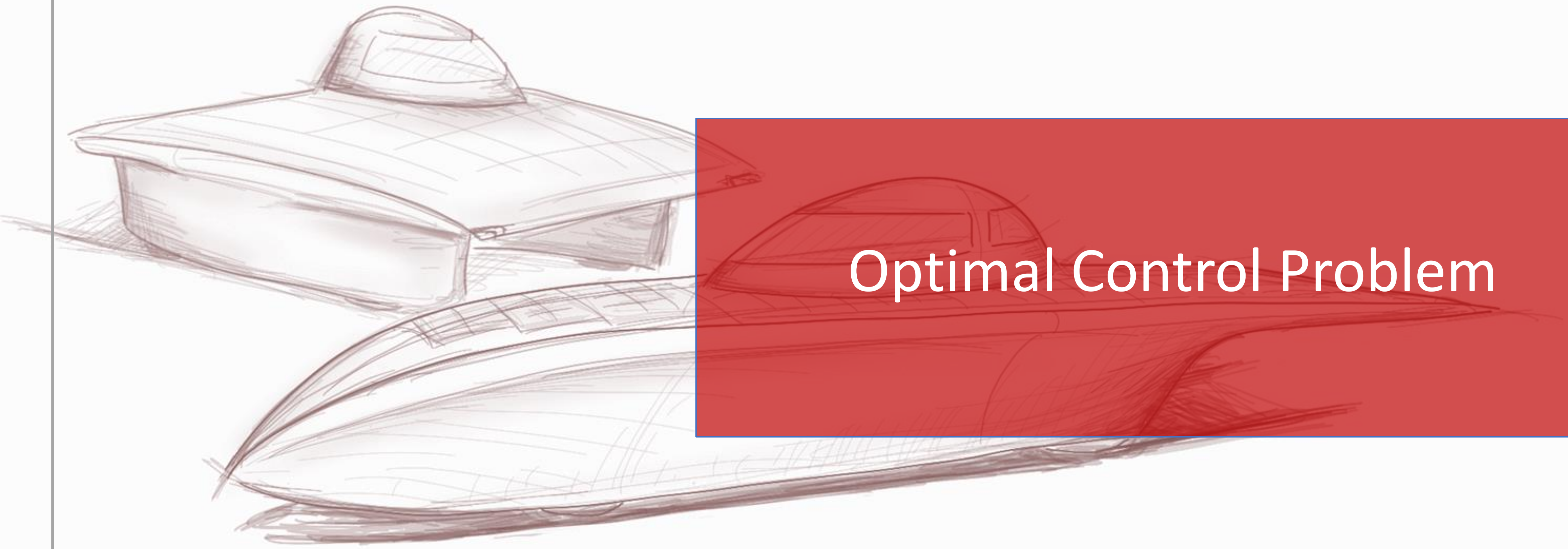


Optimal Control Problem

Optimal Control Problem

$$\min_{u(t)} J(u(t))$$

s.t.

$$\dot{x}(t) = F(x(t), u(t), t)$$

$$x(0) = x_0$$

$$x(t_f) \in [x_{f,min}, \; x_{f,max}]$$

$$x(t) \in \mathcal{X}(t) \subset \mathfrak{R}^n$$

$$u(t) \in \mathcal{U}(t) \subset \mathfrak{R}^m$$

(1) Cost Function → $J = min_{P_{\text{mot,el}}} \int_0^t dt = min_{P_{\text{mot,el}}} \int_0^x \frac{1}{v} dx$

(2) System Model → Done

(3) Initial Conditions → Simple: $SoC = 100\%; t = 0; x = 0$

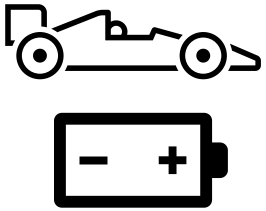
(4) Final Conditions → Simple: $x = 3000km$

(5) State Constraints → ?

(6) Input Constraints → ?

State and Input Constraints

State Constraints

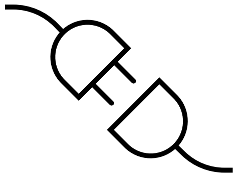


$$v_{\min}(x) \leq v \leq v_{\text{street}}(x)$$

$$SoC \geq 10\%$$

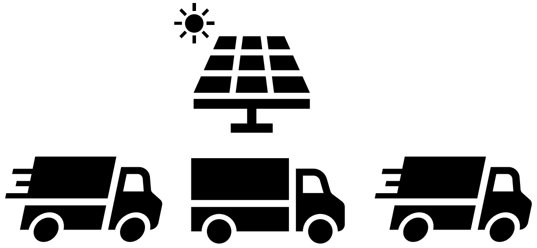
$$8{:}00 \leq t \leq 17{:}00$$

Input Constraint



$$-5kW \leq P_{\text{mot,el}} \leq 5kW$$

Stop Constraints



$$if\ x = [Stop1, Stop2, \ldots]$$

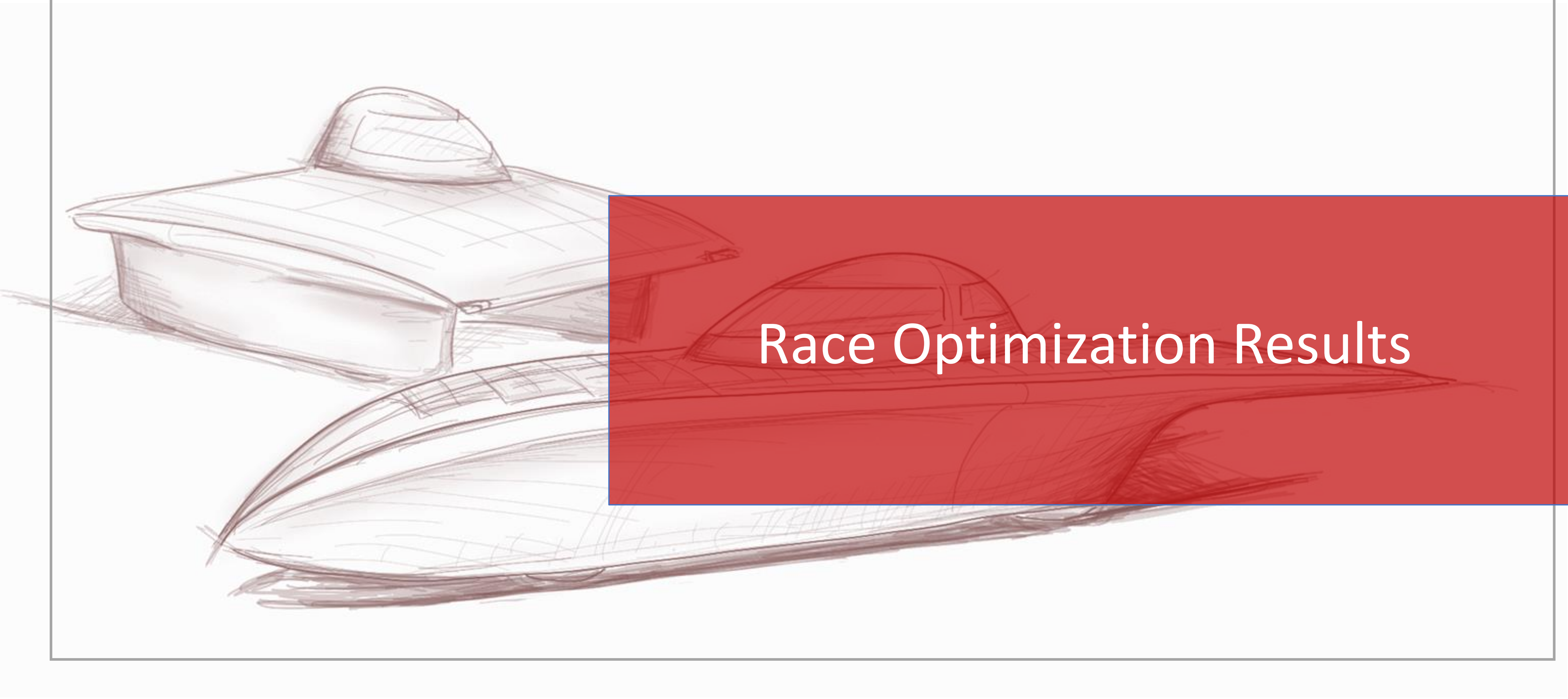
$$Contol\ Stop\ (CS)\ condition$$

$$if\ t = 17{:}00$$

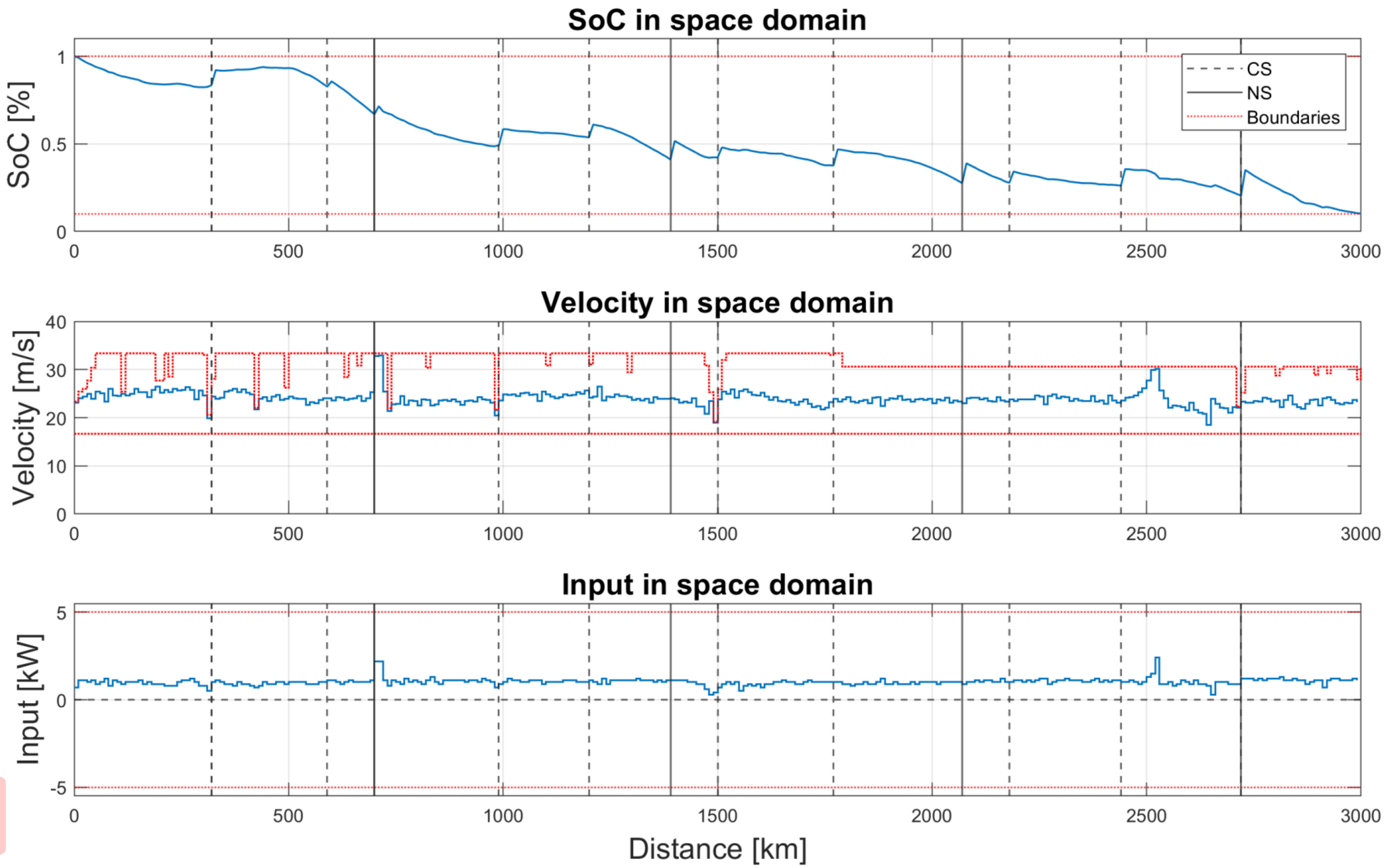
$$Night\ Stop\ (NS)\ condition$$

SOLAR RACING

Race Optimization Results



Results: Optimization of whole race

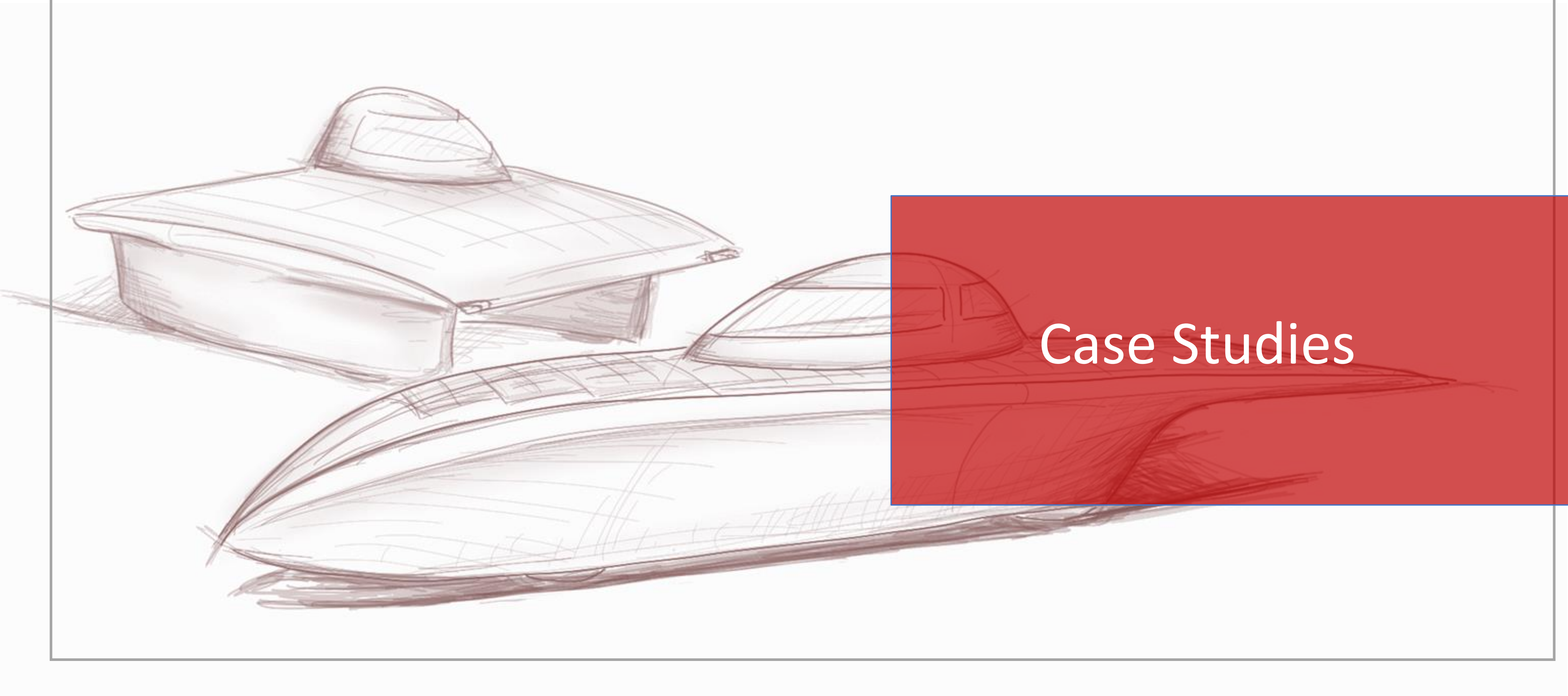


Notes:

- CSs and NSs can clearly be seen changing the SoC
- Quite steady velocity/input
- Optimizes exactly to SoC final = 10%
- Race time: 39h 26min
- Mean velocity: 86.1km/h

Distance optimized: 3000km

Computation time: 9h 30min



Case Studies

Introduction Case Studies

Goal

- Check if the output of the optimization behaves as expected when changing parameters

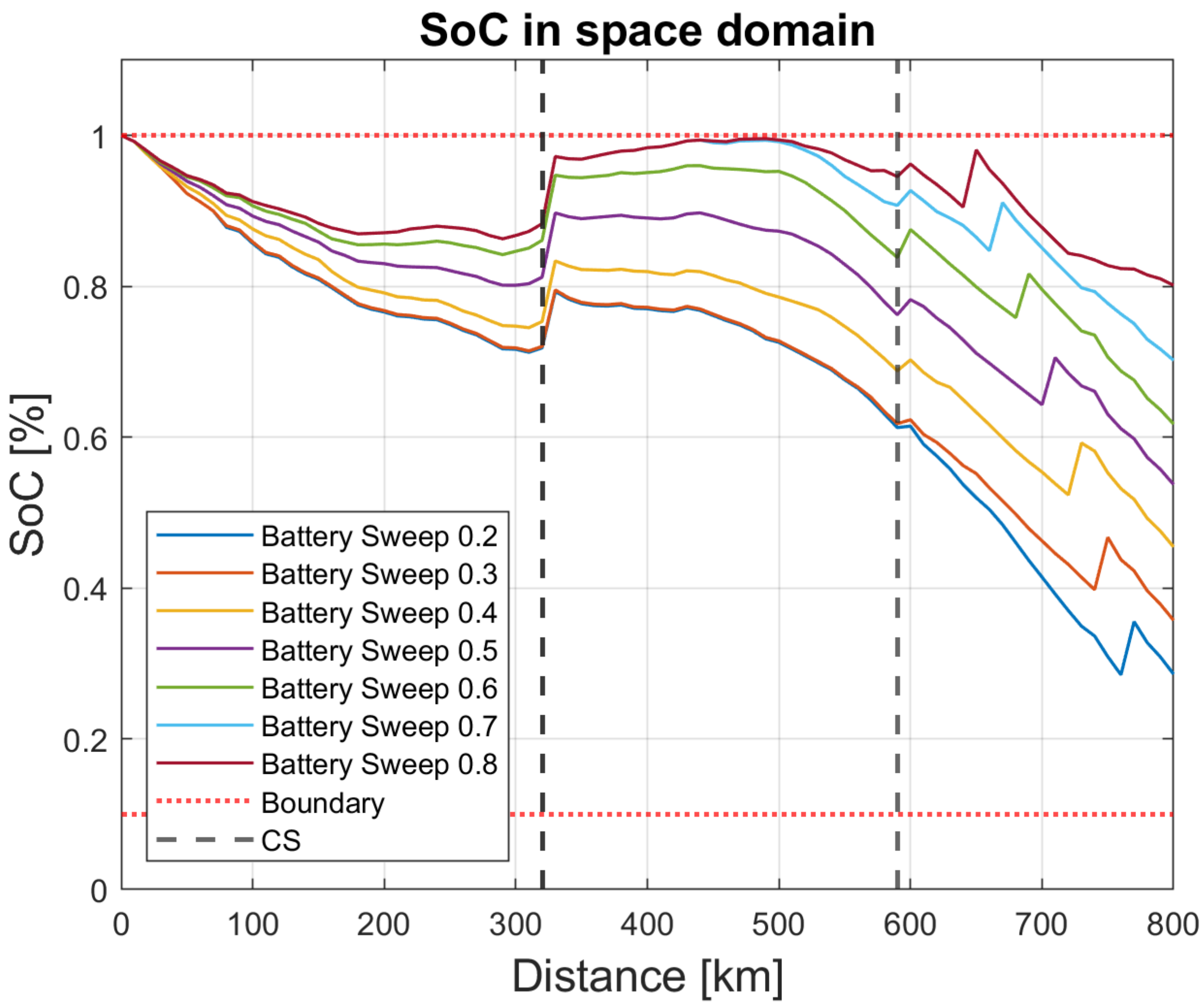
Validation through correlation

- The following validation values to assess the impact of parameter changes are chosen:
  - Final race time
  - Final state of charge
  - Average velocity
  - Average input

Case 1: Battery sweep

Setup:
- Final position = 800km

Case study parameter:
- Changing value of target SoC



Distance optimized: 800km

Computation time: 10min per iteration

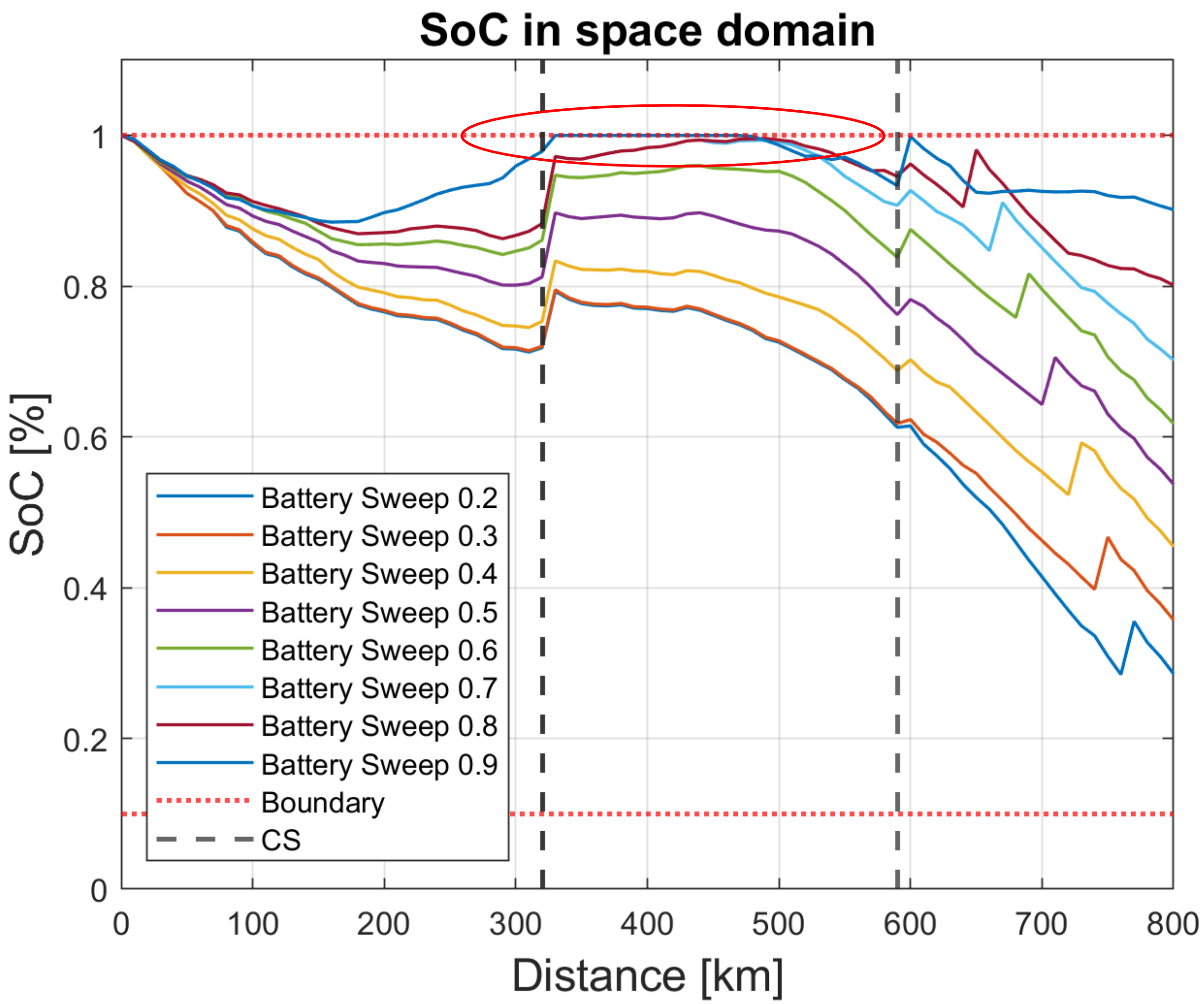
Case 1: Battery sweep

Note:

- Hitting the upper battery constraint and letting the energy storage saturate changes the solution drastically

Distance optimized: 800km

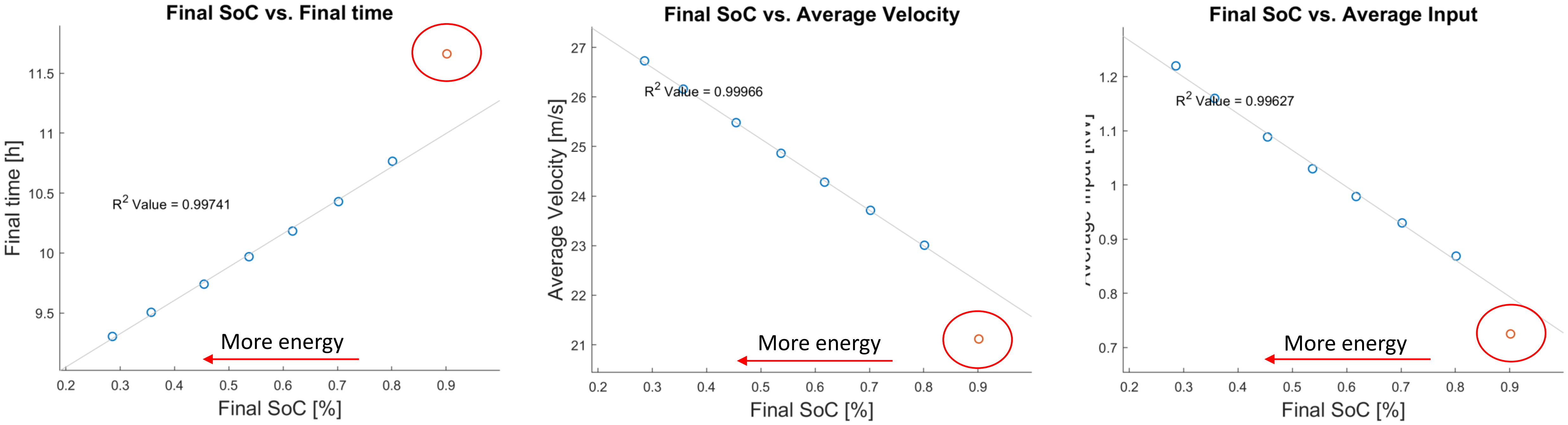
Computation time: 10min per iteration



Case 1: Correlation

Notes:
- Behaves as expected: Very good linear correlation in relevant cases
- Outlier due to battery saturation

Validation trough correlation
- Final race time (Check)
- Final SoC (Case study parameter)
- Average velocity (Check)
- Average input (Check)



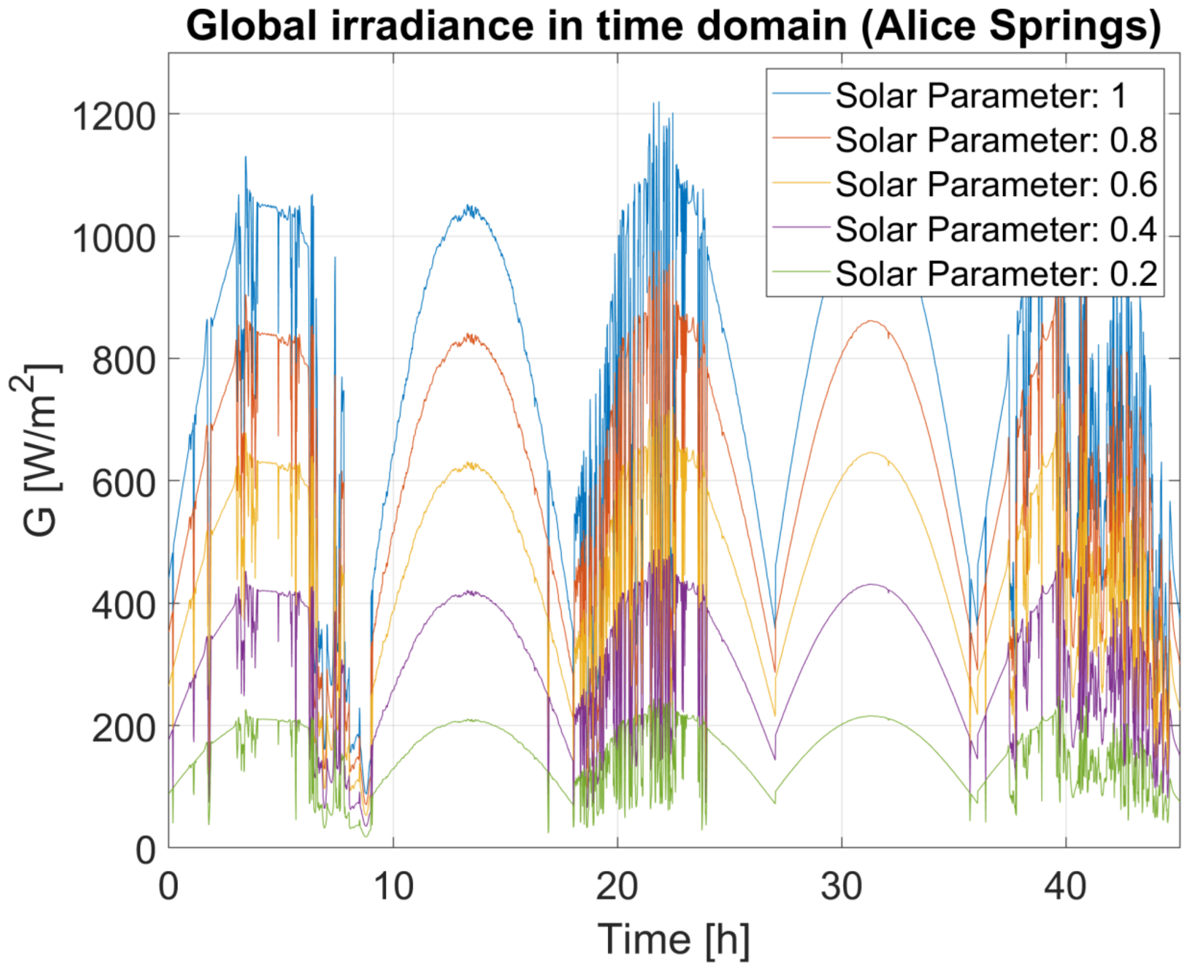
Case 2: Solar parameter sweep

Setup:

- Final position = 800km

Case study parameter:

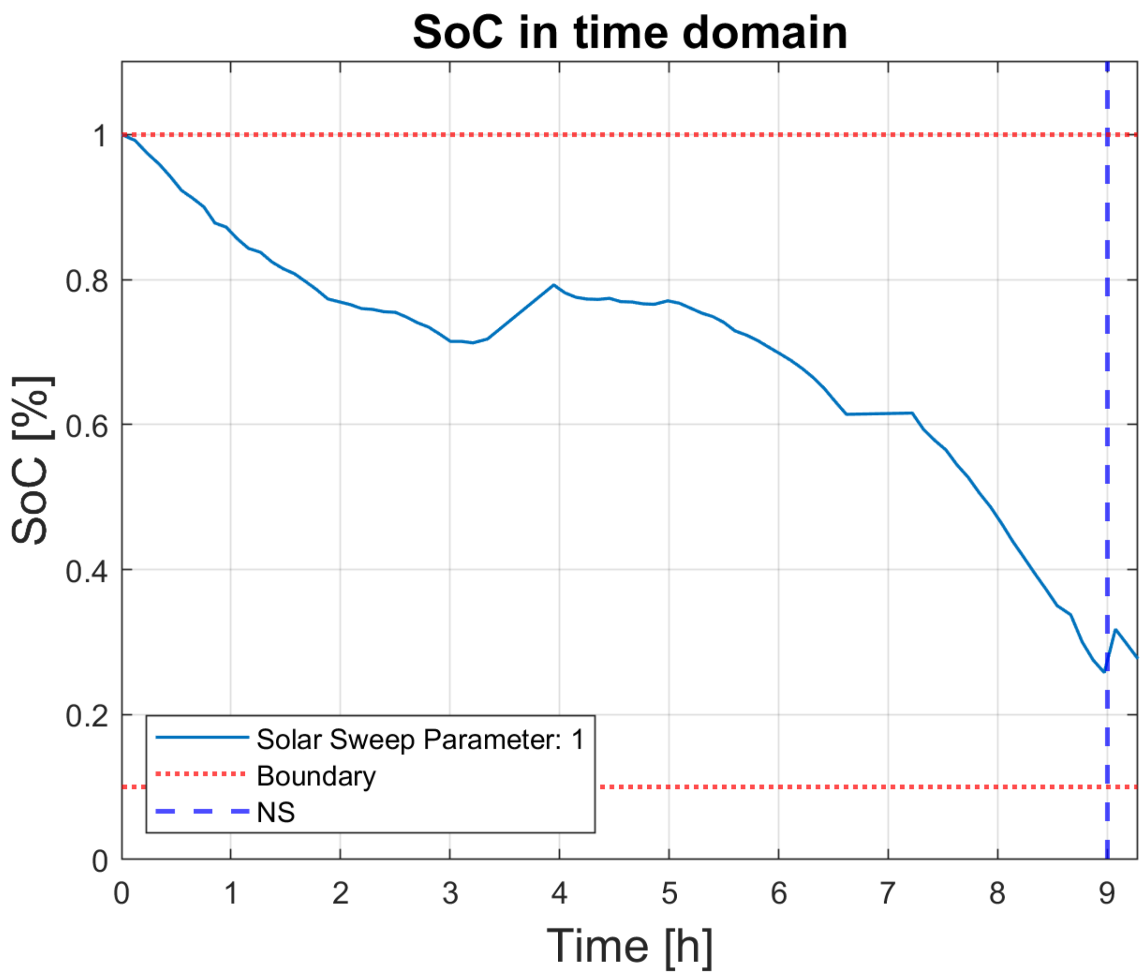
- Scaling global irradiance by multiplying it with a factor of 1, 0.9, 0.8, …
- Slowly starves system of energy



Case 2: Solar parameter sweep

Note:

- System is not energy-constrained and can always choose the highest velocity possible (final SoC > 10%)



Distance optimized: 800km

Computation time: 10min per iteration

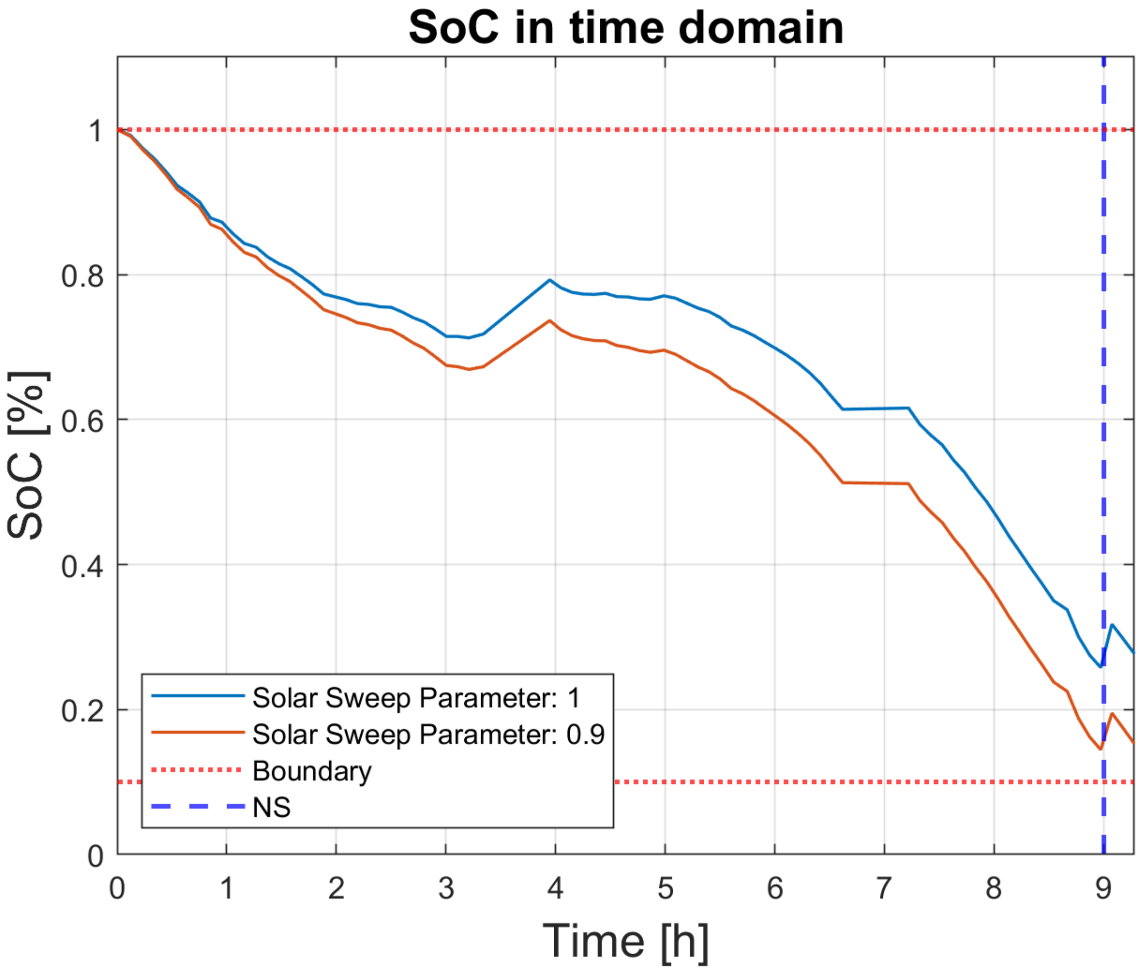
Case 2: Solar parameter sweep

Note:

- System is not energy-constrained and can always choose the highest velocity possible (final SoC > 10%)
- Second solution has less energy available and therefore punishes the SoC final state

Distance optimized: 800km

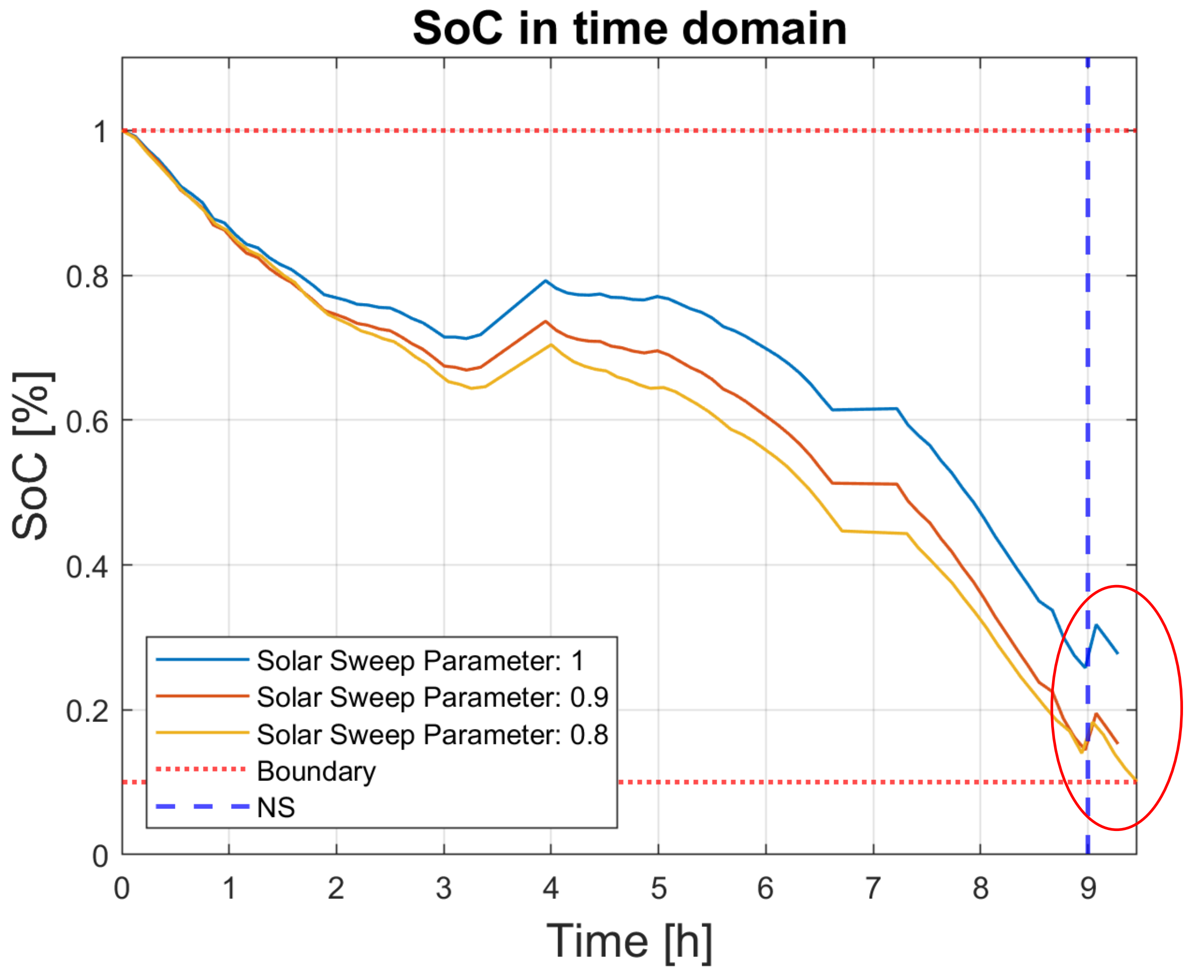
Computation time: 10min per iteration



Case 2: Solar parameter sweep

Note:

- System starts to be energy-constrained and needs to actually optimize the behavior (final SoC = 10%)
- Third solution has even less energy available and is now forced to punish the final time state



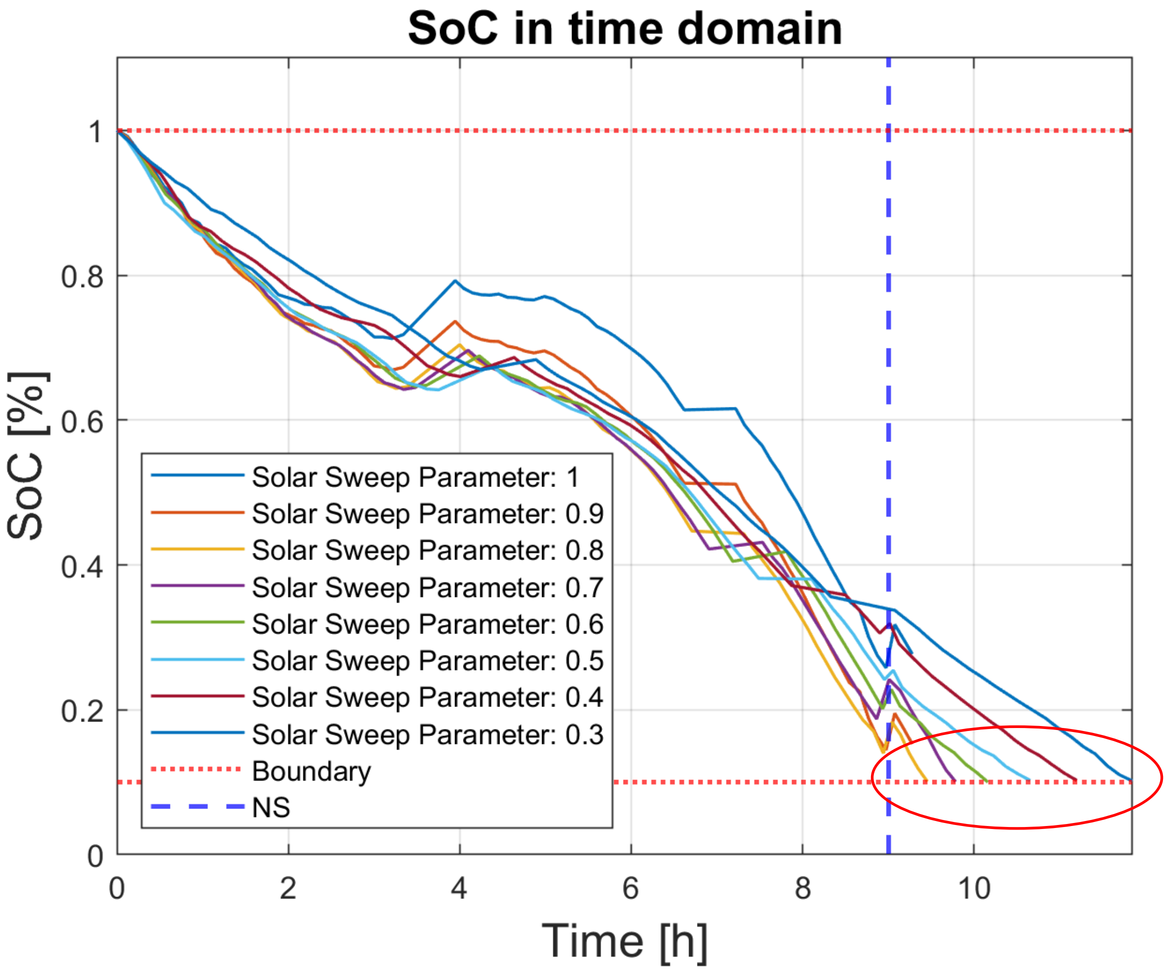
Distance optimized: 800km

Computation time: 10min per iteration

Case 2: Solar parameter sweep

Note:

- System starts to be energy-constrained and needs to actually optimize the behavior (final SoC = 10%)
- The trend continues for the rest of the solutions: less energy, more time is needed to reach the destination



Distance optimized: 800km

Computation time: 10min per iteration

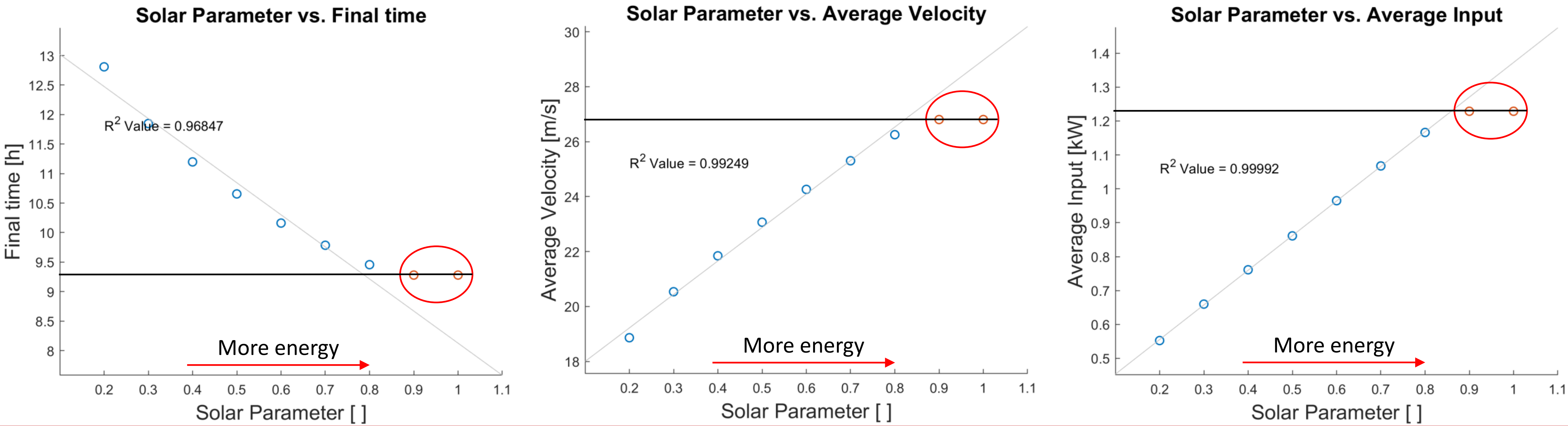
Case 2: Correlation

Validation trough correlation

- Final race time (Check)
- Final SoC (Always tracks to 0)
- Average velocity (Check)
- Average input (Check)

Notes:

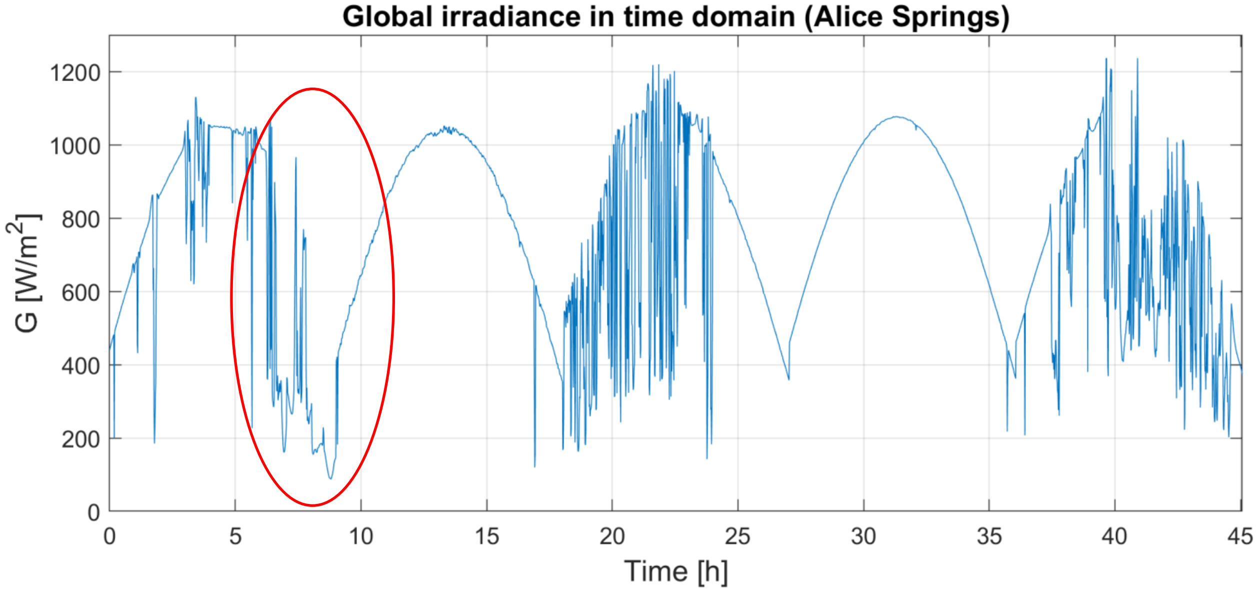
- Behaves as expected: Good linear correlation
- Outliers due to non-energy-constrained sweeps
- 0.2 optimization struggles to keep up (<0.2 not possible)

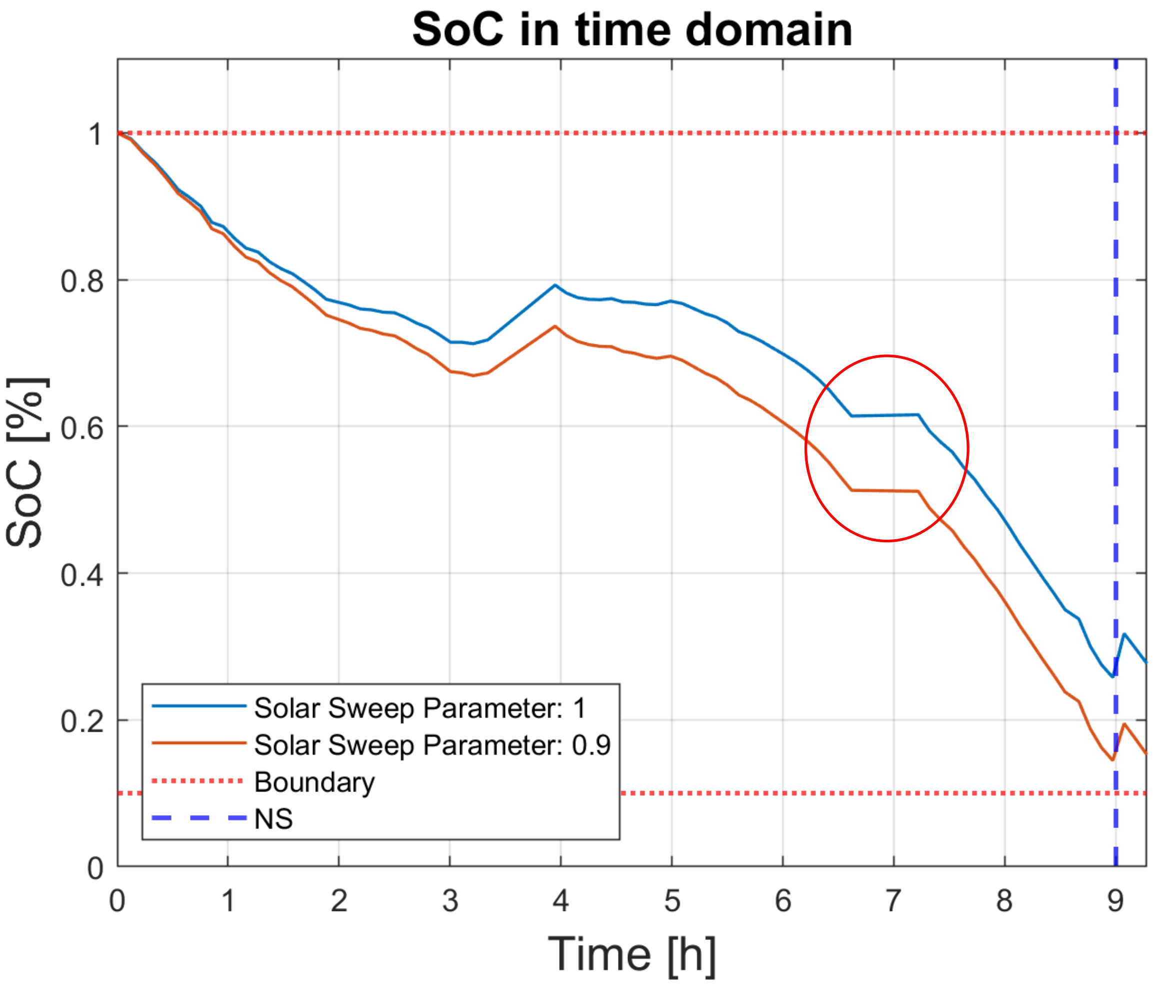


Case 2: Sidenote

Note:

- Why is the SoC seemingly staying constant during the second CS?
- Car still drives 10km and gets very little solar energy (both cancel out)





Case 3: Solar "wall" sweep

Setup:

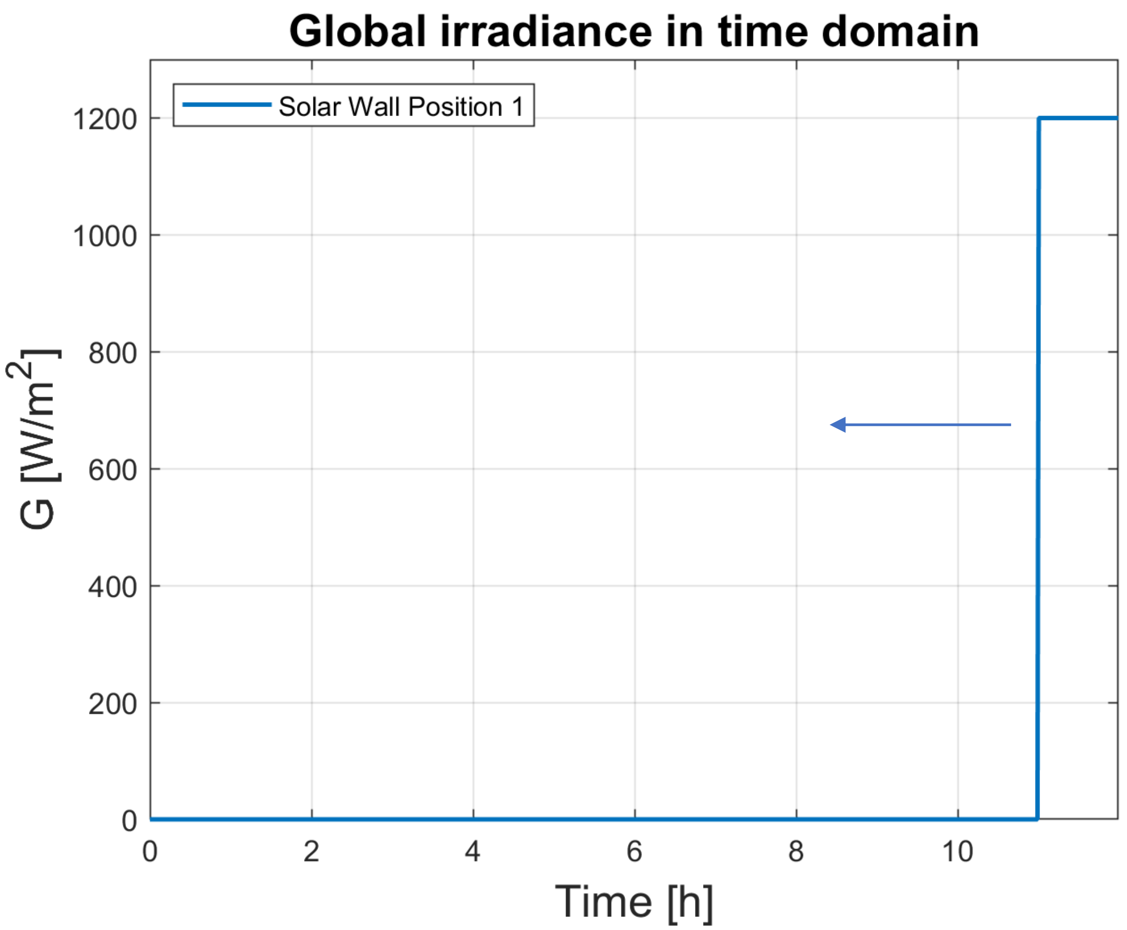
- Final position = 800km

Case study parameter:

- Solar irradiance is modeled as a step function from 0 to 1200 W/m2
- Parameter moves step 30min to the left each iteration

Distance optimized: 800km

Computation time: 10min per iteration



Case 3: Solar “wall” sweep

Setup:

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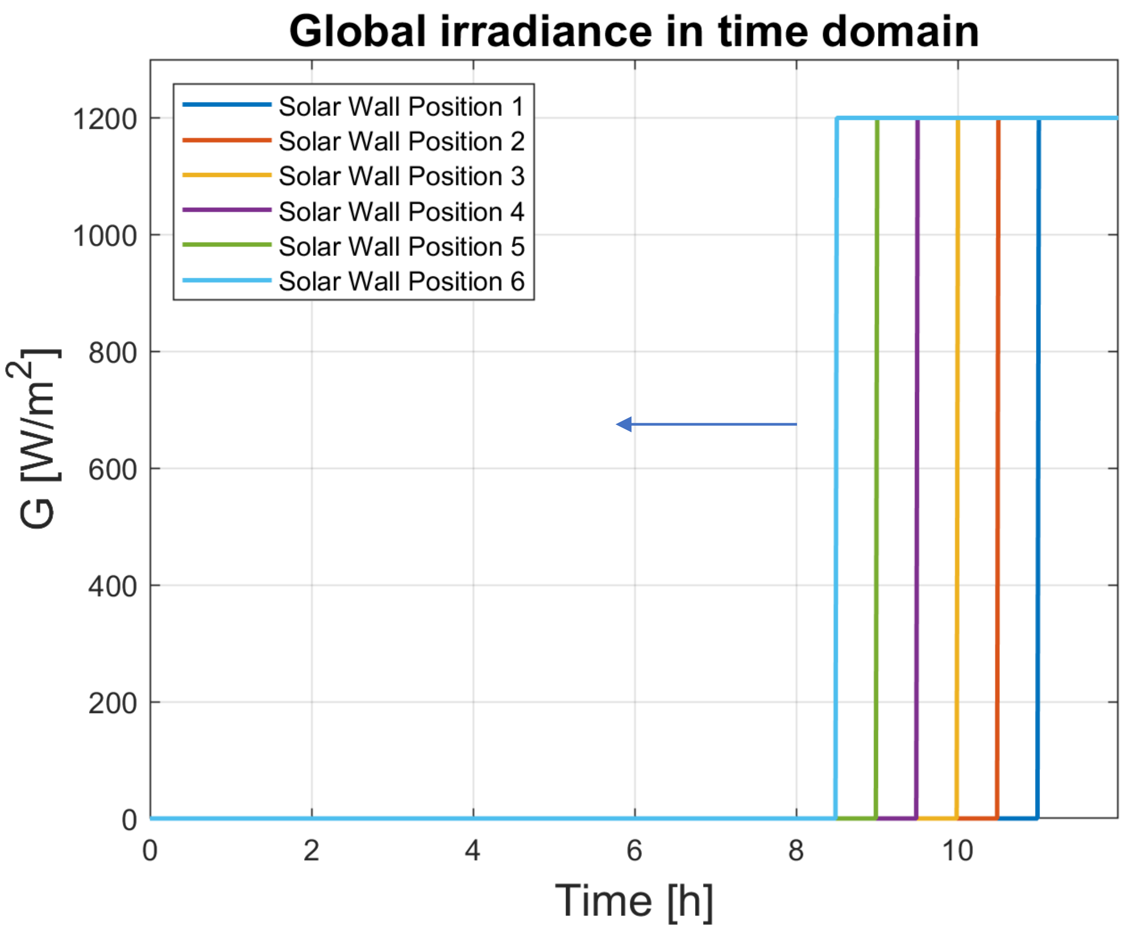
Computation time: 10min per iteration

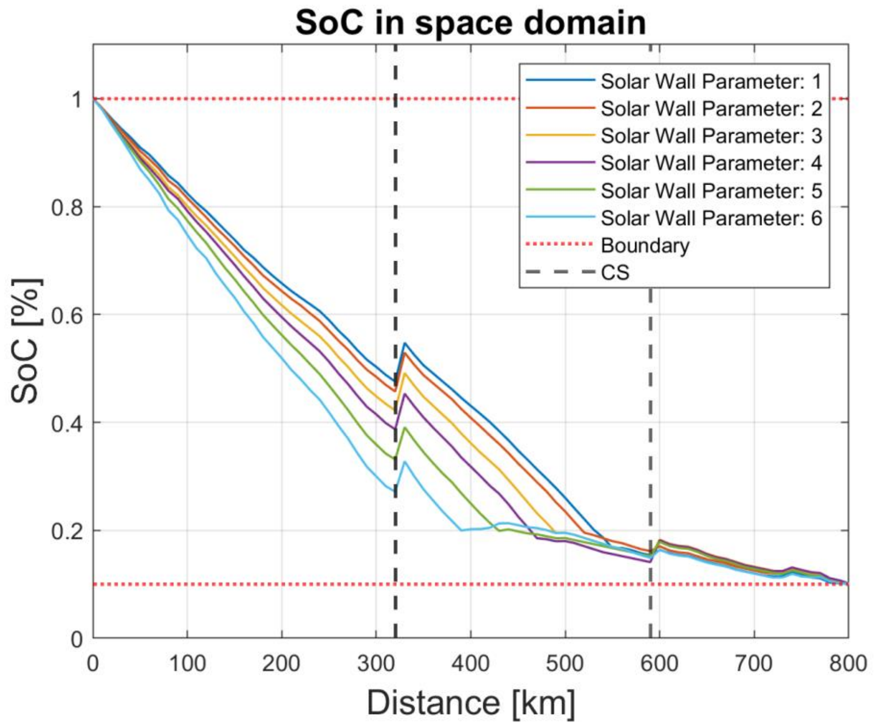


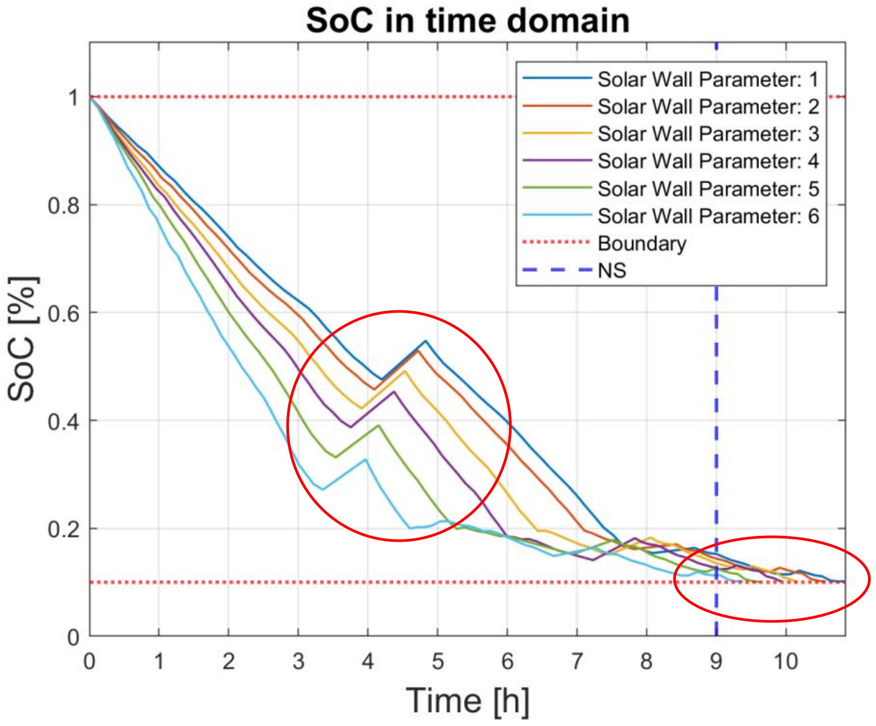
Case 3: Solar "wall" sweep

Note:
- System is energy starved and punishes final time
- "Wall" can be seen moving in the time domain

Distance optimized: 800km

Computation time: 10min per iteration

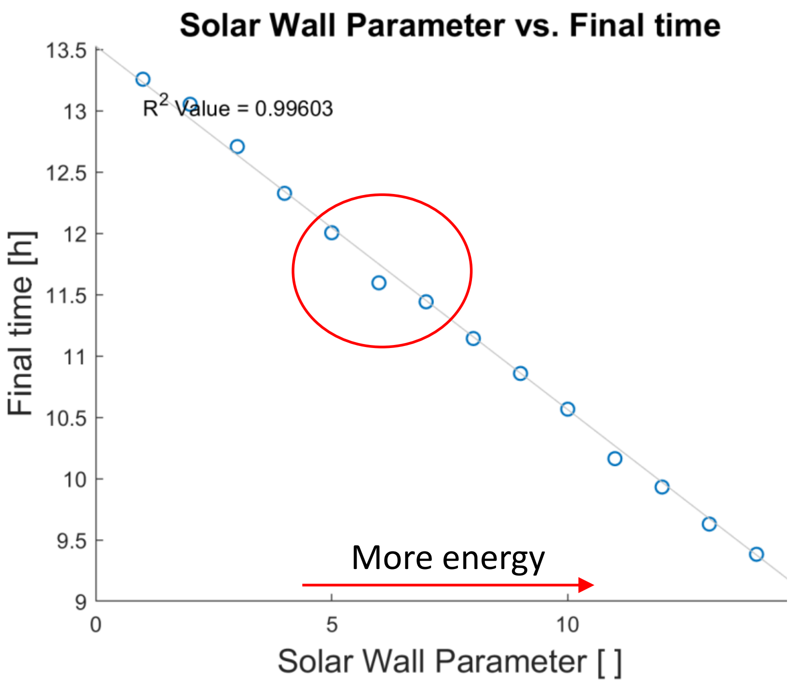


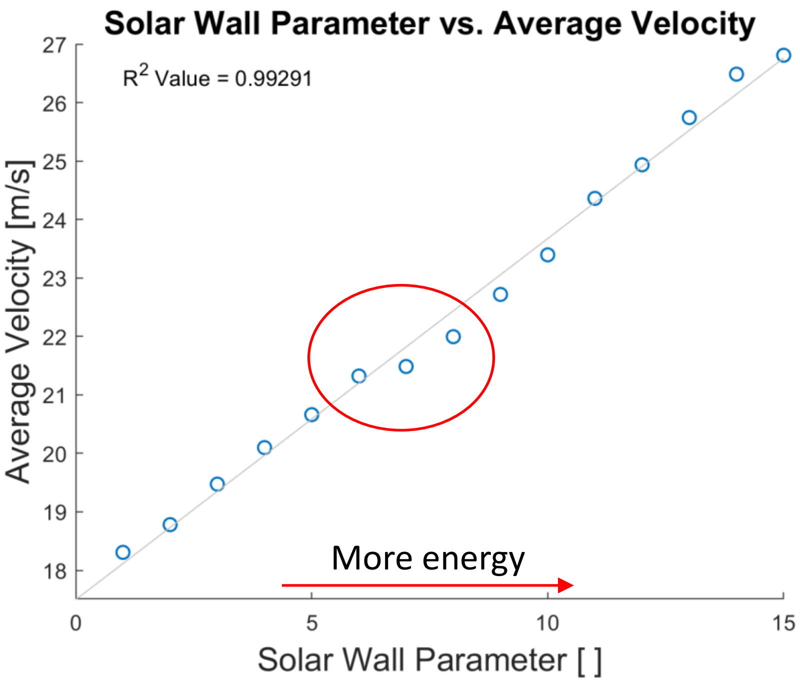


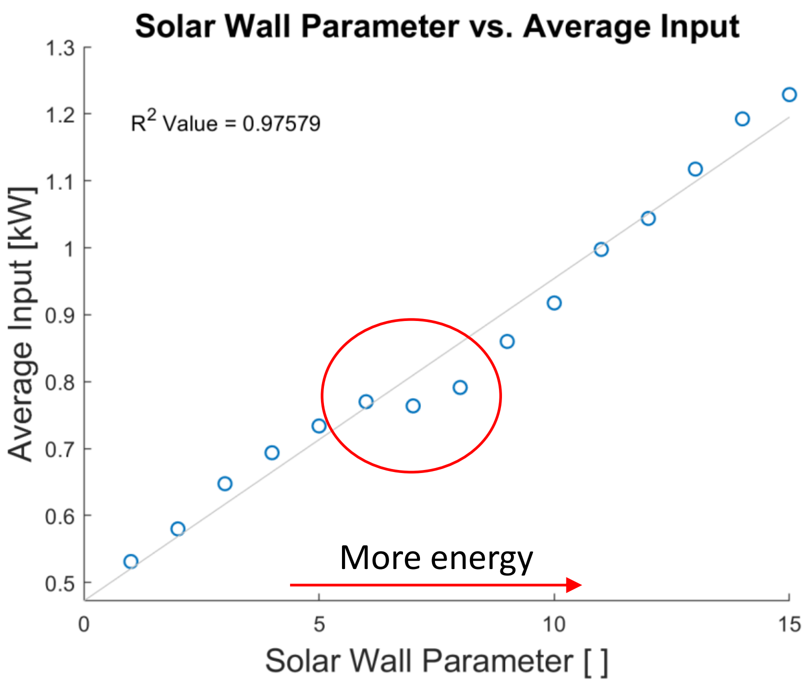
Case 3: Correlation

Notes:
- Behaves as expected
- Linear correlation changes slightly around parameter 7 due to Control Stop dynamics

Validation trough correlation
- Final race time (Check)
- Final SoC (Always tracks to 0)
- Average velocity (Check)
- Average input (Check)







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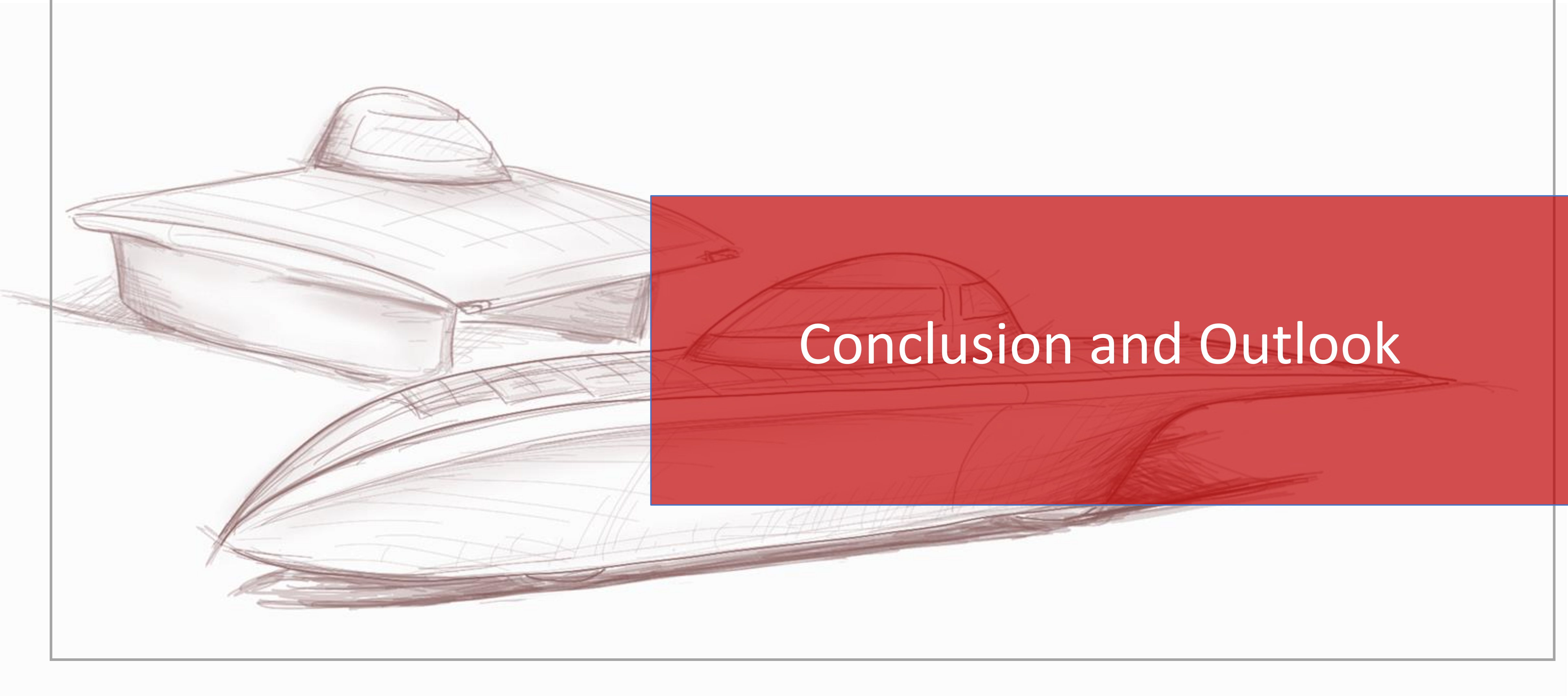

Conclusion and Outlook

Conclusion and Outlook

Conclusion

- Optimal race strategy found
- Versatile algorithm for future races, other competitions and different car designs
- Optimization successfully validated through correlation with case studies

Outlook

- Improving models (e.g., PV temperature)
- Adding space dependence for global irradiance (currently only time dependent due to lack of data)
- Short-term strategy with higher resolution and frequent strategy updates using Model Predictive Control (optimizing in-between CSs and NSs)
- Implementation of tilt conditions for car
- Validation with real race data

Thank you for joining the presentation!

Q&A