# Analysis, Design and Optimization of a Drag Reduction System

Cong Thuong Pham, Dalle Vedove Matteo, Serrao Joel

A.Y. 2021-2022

University of Trento - Department of Industrial Engineering

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# Reference car

Major data taken from the ***Perrin F1 2017*** prototype car; for simulations are considered: mass of the car $m = 780kg$, mass of fuel $\simeq 40kg$, driver mass $\simeq 80$. Overall

$$m_{car} = 900kg$$

Comparison data have beeen taken from telemetries of *Assetto Corsa* videogame using *Ferrari SF70H* car.

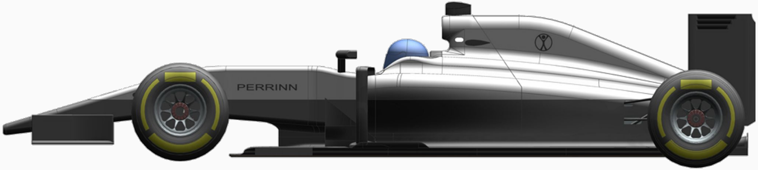


**Figure 1:** PERRIN F1 2017 prototype car.

# Model of the motor

Engine datas:

| Speed | Torque |
|---|---|
| $5000 RPM$ | $650 N \cdot m$ |
| $6000 RPM$ | $650 N \cdot m$ |
| $7000 RPM$ | $645 N \cdot m$ |
| $8000 RPM$ | $640 N \cdot m$ |
| $9000 RPM$ | $640 N \cdot m$ |
| $10\,000 RPM$ | $640 N \cdot m$ |
| $11\,000 RPM$ | $635 N \cdot m$ |
| $12\,000 RPM$ | $600 N \cdot m$ |
| $13\,000 RPM$ | $550 N \cdot m$ |
| $14\,000 RPM$ | $460 N \cdot m$ |
| $15\,000 RPM$ | $390 N \cdot m$ |

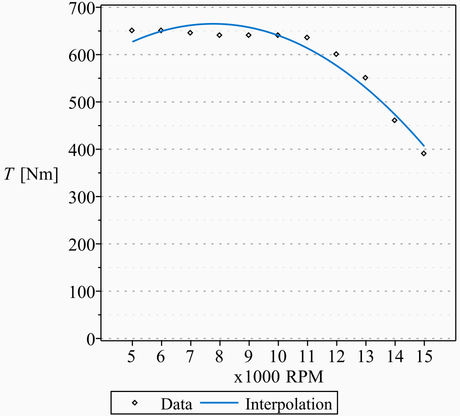


**Figure 2:** motor torque vs RPM - tabled data and quadratic fitting.

# Model of the generated forces

Efficiency of the power transmission:

$$\eta = 95\%$$

Gear ratio:

$$\tau_{gear} = \frac{\omega_{motor}}{\omega_{wheel}} = 4.8615$$

Wheel radius:

$$r = 0.33m$$

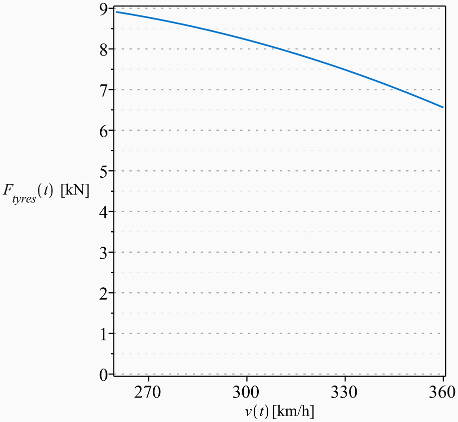


**Figure 3:** force generated by the tyres vs car velocity using the fitted torque model.

## Aerodynamic forces on the car

Given aerodynamic forces of type $F = \frac{1}{2}\rho C S v^2$, CFD simulation in freestream condition at $v = 50 m/s$:

$$CS_{drag} = 1.16 m^2 \qquad CS_{down} = 3.35 m^2$$

In simulations different behaviours have been considered:

| **Condition** | **Drag coefficient** | **Downforce coefficient** |
|---|---|---|
| low drag | 1.08 | 3.63 |
| mid drag | 1.34 | 4.35 |
| high drag | 1.61 | 5.16 |

Considered air density $\rho = 1.225 kg/m^3$.

# Aerodynamical forces models

Profiles functions obtained by the paper from *Dimastrogiovanni*. Results have been polynomially fitted and rescaled accordingly to match the *PERRIN* model. For rescaling purposes it has been considered that the total drag and lift coefficients on the rear wing (mainplane + flap) are

$$CS_{drag} = 0.235m^2 \quad CS_{down} = 0.92m^2$$

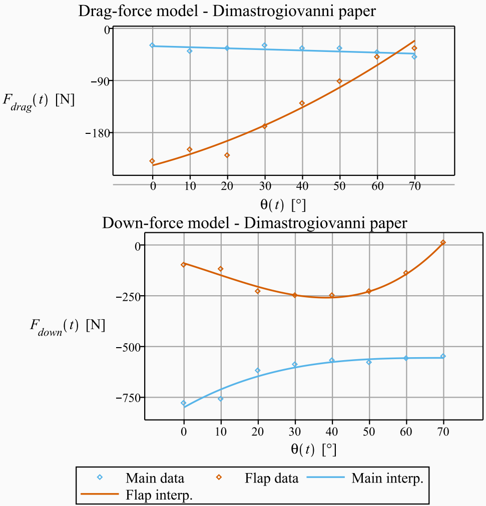


**Figure 4:** drag (upper) and down force (lower); mainplane in blue, flap in red.

# Steady state velocity

Considering:

- first rolling resistance coefficient $f_0 = 0.025$
- second rolling resistance coefficient $K = 6.5 \cdot 10^{-6} s^2/m^2$

Gives the equilibrium velocity that's reached asymptotically.

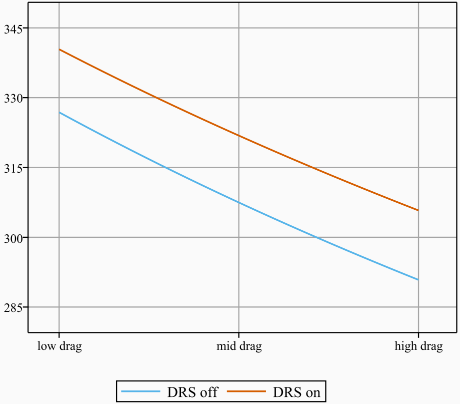


**Figure 5:** steady state velocity depending on the drag condition and DRS close (blue) or open (red).

## Kinematic Analysis

Common data to all mechanisms:

- Ground frame is positioned in the rear wheel;
- Pivot point of the moving tether in $(x_{flap}, y_{flap}) = (555, 525)mm$;
- Rotation is described by the vertical direction with $\theta$; to be compliant with regulation: $\theta_{min} = 45°$, $\theta_{max} \leq 70°$;
- Flap as a simple bar of length $L_{flap} = 200mm$.

The modelling approach used is mainly recursive.

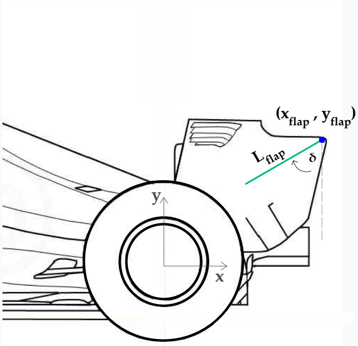


**Figure 6:** common reference frame.

# Push-up mechanism

The L-shaped body dimension are chosen after iterative process.

Kinematic coordinates:

- stroke $s(t)$;
- flap angle $\theta(t)$.

Constraints:

- rod joint.

Optimization variables:

- $L_{link}$ rod-joint length;
- $s_{max}$ maximum stroke;
- $L_{2x}, L_{2y}$ dimensions of the support;
- $\delta_{cyl}$ inclination of the cylinder.

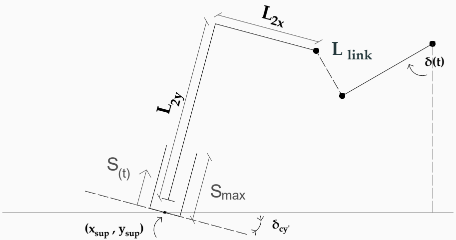


**Figure 7:** common reference frame.

# Push-up mechanism: Preliminary minimization

Minimization performed using Maple's *non-linear simplex* method; all constraints have been model as terms penalizing an objective function.

| **Parameter** | **Value** |
|---|---|
| $L_{link}$ | $106.33mm$ |
| $s_{max}$ | $80.22mm$ |
| $\delta_{cyl}$ | $-1.61°$ |
| $L_{2x}$ | $166mm$ |
| $L_{2y}$ | $315mm$ |

It has been considered $(x_{cyl}, y_{cyl}) = (200mm, 200mm)$.

# Push-up mechanism: Minimization plots

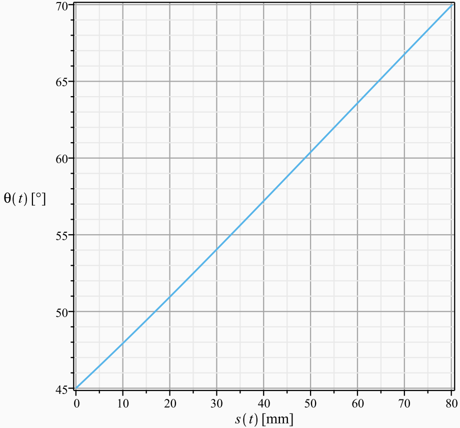


**Figure 8:** flap angle vs stroke.

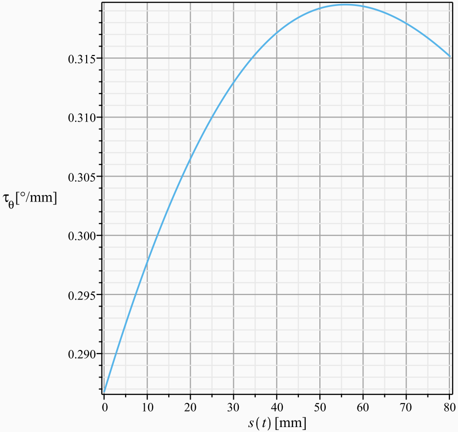


**Figure 9:** velocity ratio of the flap angle vs stroke.

We use the **Newton - Euler** approach to perform the dynamic analysis of the system.

- There are four main forces acting on the system, viz., drag force ($F_{drag}$), down force ($F_{down}$), torque due to the wind ($T_{flap}$) and the actuator force due to the hydraulic cylinder ($F_{act}$).
- We have 5 reaction forces: $R_{jx}, R_{jy}$ due to the revolute joint at the flap, $F_{link}$ due to the tension of the link, $P_{jx}, P_{jz}$ due to the prismatic joint.

We observe that the number of equations (1 constraint and $3 \cdot 2$ Newton-Euler equations) matches the number of variables (2 coordinates and 5 reactions).

## Diameter of the cylinder

The diameter of the cylinder has been computed using the principle of virtual work. Computing the maximum force of the actuator and given the maximum pressure of the circuit, the minimum allowed diameter is computed.

For the simulation we considered a diameter $D = 7mm$ that's 50% higher then the minimum allowed value.

# Hydraulics specifications

Formula cars are equipped with aerospace-grade hydraulic components. Honda F1 engine from 2017 mounts a *Parker AP05V* variable displacement axial piston pump with a maximum flow of $25.7 l/min$ and maximum pressure of $207 bar$.

In the following simulations the flow is reduced to $12 l/min$ considering that the fluid usage is shared with the whole car.

# Hydraulic circuit: Simulink blocks

1. Hydraulic flow rate source: ideal component that provides the input flow inside the chamber of the hydraulic cylinder.


**Figure 10:** Simulink icon of the hydraulic flow rate

2. Presure relief valve: used to set the maximum pressure of the hydraulic circuit to the safety value of $p_{max} = 207 bar$.


**Figure 11:** Simulink icon of the pressure relief valve

# Hydraulic circuit: Simulink blocks

3. Double-acting hydraulic cylinder: used to actuate the prismatic joint with force. Area $\frac{\pi}{4}D^2$ of cylinder $A$ depends on diameter computed by the minimization as well as the stroke.

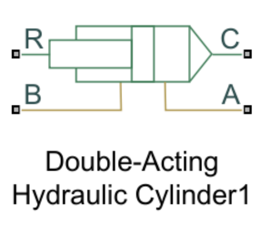


**Figure 12:** Simulink icon of the double acting hydraulic cylinder

4. Translational multibody interface: used to connect the hydraylic cylinder (translational mechanical domain) with the prismatic joint (multibody domain).

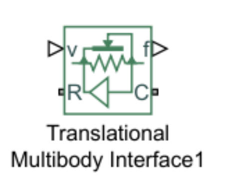


**Figure 13:** Simulink icon of the translational multibody interface

# Hydraulic mechanism: Simulink circuit

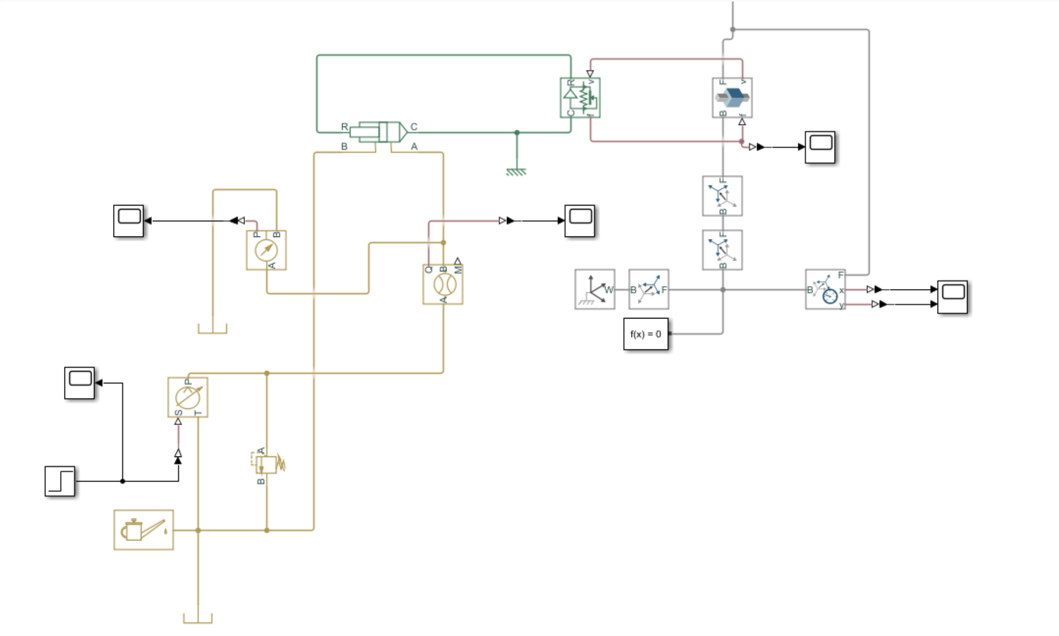




Figure 14: Hydraulic system

## Simulation results: advantage of the DRS

With the model provided, simulations have been performed considering an initial velocity of the car $v_0 = 260 km/h$. The simulation lasts $10s$ and the DRS opens after $2s$.

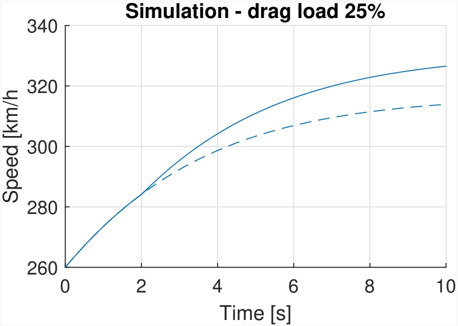


**Figure 16:** medium-low drag case.

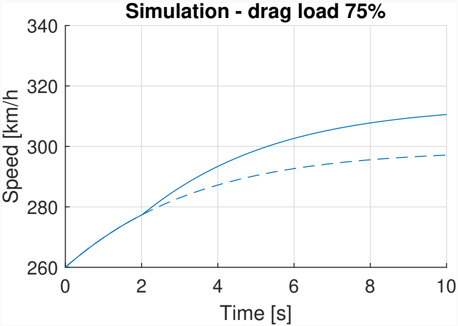


**Figure 17:** medium-high drag case.

The distance traveled are respectively $846m, 816m$ and the activation of the DRS provides a gain of $18m, 20m$.

# Simulation results: advantage of the DRS

With the model provided, simulations have been performed considering an initial velocity of the car $v_0 = 290 km/h$. The simulation lasts $10s$ and the DRS opens after $2s$.

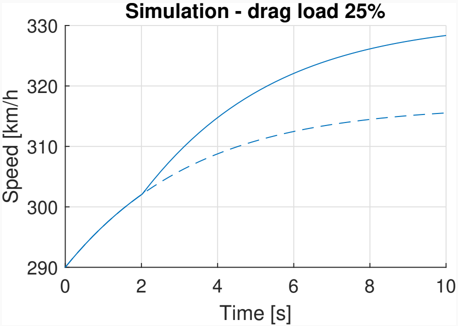


**Figure 18:** medium-low drag case.

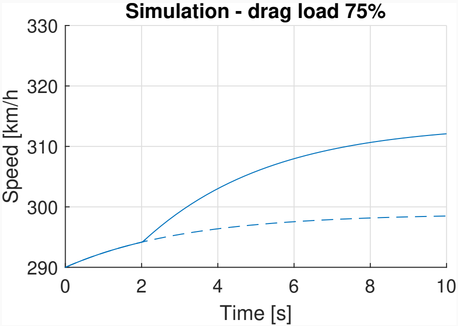


**Figure 19:** medium-high drag case.

The distance traveled are respectively $875, 843m$ and the activation of the DRS provides a gain of $19m, 20m$.

The system has been compared with the telemetries provided by the game *AssettoCorsa 2017*. Here we compare runs with no DRS activation.

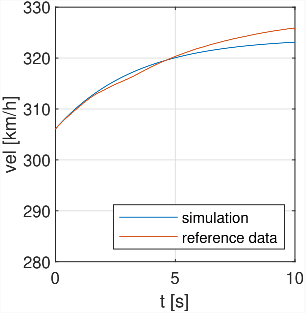


**Figure 20:** low drag, 7%.

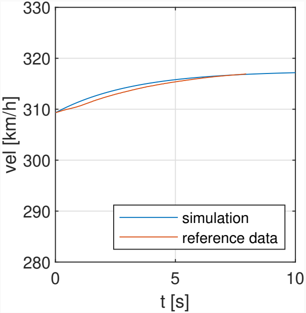


**Figure 21:** medium drag, 23%.

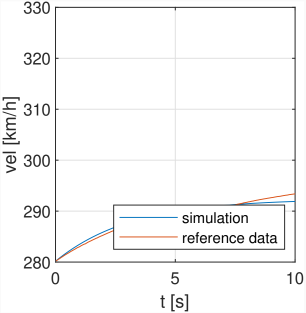


**Figure 22:** high drag, 95%.

# Comparison with *AssettoCorsa 2017*

The system has been compared with the telemetries provided by the game *AssettoCorsa 2017*. Here we compare runs with DRS activation.

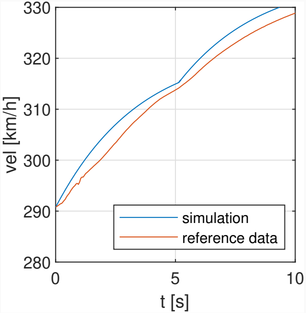


**Figure 23:** low drag, 12%.

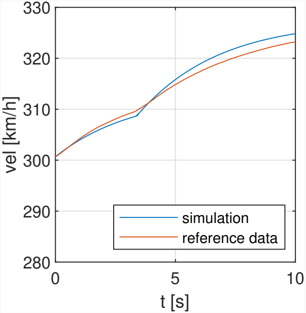


**Figure 24:** medium drag, 35%.

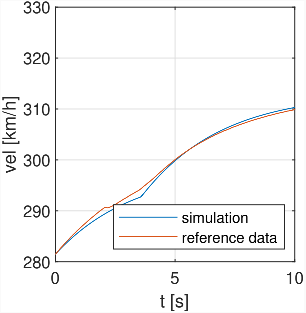


**Figure 25:** high drag, 77%.

## Behaviour of the mechanism

Simulation performed considering an initial velocity $v_0 = 290 km/h$, drag load 30%; DRS activates after $2s$, simulation of $10s$.

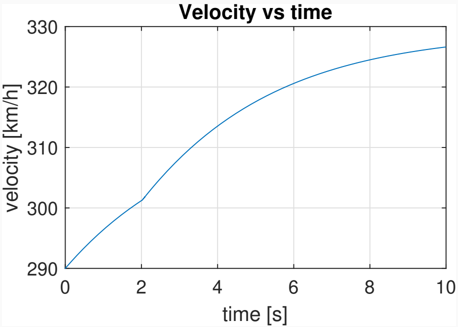


**Figure 26:** velocity profile over time.

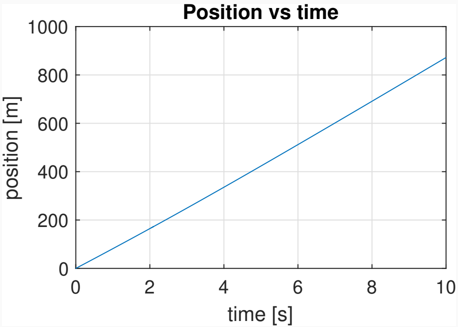


**Figure 27:** position profile over time.

# Behaviour of the mechanism

Simulation performed considering an initial velocity $v_0 = 290 km/h$, drag load 30%; DRS activates after $2s$, simulation of $10s$.

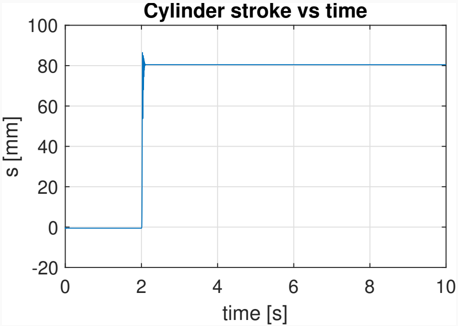


**Figure 28:** stroke of the cylinder over time.

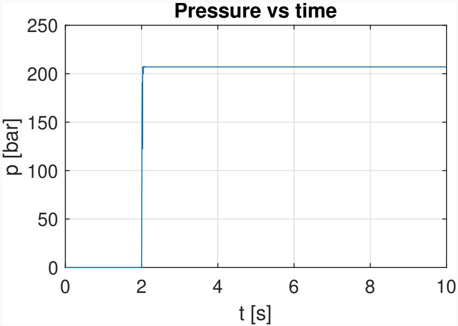


**Figure 29:** pressure inside the cylinder over time.

While actuating, pressure reaches a maximum value of $190 bar$, then it stabilizes at $207 bar$ set by the pressure relief valve.

# References


- *Aerodynamics of a 2017 Formula 1 car: Numerical Analysis of a Baseline Vehicle and Design Improvements in Freestream and Wake Flows*, Umberto Ravelli, Università degli Studi di Bergamo, Department of Engineering and Applied Sciences
- *An improved active drag reduction system for formula race cars*, Mauro Dimastrogiovanni, Giulio Reina, Andrea Burzoni, IMechE 2019, Journal of Automobile Engineering.
- *2022 Formula 1 Technical Regulation*, issue 10, FIA
- *F1 Hydraulic Pump, a closer look*, f1technical.net