

White Paper

PARIS HYBRID^{TM} Drivetrain:
Accelerating the Decarbonization of Commercial Vehicles

Published by 4QT Holding AG

Marc M. Vetter, MSc. ETH Zürich

Uygar Pala, Dr. sc. ETH Zürich

Q4 2022 v1.1

Table of Contents

1 Introduction **3**

2 Background and Motivation **3**

3 Assumptions **3**

4 Relative Rate of Fuel Consumption **4**

5 Series Hybrid Drivetrain **6**

6 Paris Hybrid^{TM} Drivetrain **7**

7 Relative Fuel Savings of Paris Hybrid^{TM} Drivetrain **10**

8 Conclusion **12**

© 2022 4QT Holding AG. All rights reserved.

Abbreviations

Descriptor	Definition	Unit
τ	Torque	$[Nm]$
P	Power	$[W]$
ω	Angular speed	$[1/min]$
$\dot{H}$	Rate of fuel consumption	$[L/s]$
c	Fuel coefficient	$[L/Ws]$
η	Inefficiency	$[-]$
X_{DRM}	Double Rotor Machine	$[-]$
X_{SH}	Series hybrid	$[-]$
X_{4QT}	Paris Hybrid^{TM}	$[-]$
X_{motor}	Motor	$[-]$
$X_{generator}$	Generator	$[-]$
X_{eAXLE}	Separate or integrated e-Axle (stator)	$[-]$
X_{ICE}	Internal combustion engine	$[-]$
X_{EL}	Electric	$[-]$
X_{req}	Required by operator	$[-]$
X_{in}	Input	$[-]$
X_{out}	Output	$[-]$
SOC_{bat}	Battery state of charge	$[-]$
X_{SYS}	System (from ICE output to operator)	$[-]$

© 2022 4QT Holding AG. All rights reserved.

1 Introduction

The presented White Paper will establish the analytical proof of the higher efficiency of the Paris Hybrid^{TM} Drivetrain over the current series hybrid drivetrain technologies.

Initially, the definition for relative rate of fuel consumption is presented. Following, the efficiencies of series hybrid and the Paris Hybrid^{TM} drivetrain technologies are defined. In the final section, the relative fuel savings of the Paris Hybrid^{TM} drivetrain is calculated and explained for varying electric motor efficiency rates in series hybrid drivetrains.

2 Background and Motivation

1. Electrification reduces the scope three emissions of vehicles. For cars, Tesla is leading the way in changing the industry and OEMs are following. Commercial vehicles need to follow fast to reduce the climate impact of new vehicles and of those already in operation.

2. Incentives such as the Inflation Reduction Act and the Infrastructure Investment and Jobs Act enable technology advances, investment and testing of cleaner solutions.

3 Assumptions

1. Steady state operation is a reasonable first order approximation and the results are representative of the full system operation.

2. Efficiencies are constant across the relevant operating range. The compared systems react similar to environmental factors such as temperature, elevation and speed. Therefore this is a reasonable assumption to make a-priori.

3. Efficiencies of an electric machine are the same in generator and in motoring mode.

4. The losses can be summarized in such a way that a loss coefficient is obtained per energy converter.

© 2022 4QT Holding AG. All rights reserved.

4 Relative Rate of Fuel Consumption

The steady state operation suggests:

$$P_{req} = constant \tag{1}$$

$$SOC_{bat} = constant \tag{2}$$

$$\dot{H} = P_{ICE} \cdot \eta_{ICE} \cdot c_{ICE} \tag{3}$$

where P_{req} is the power required by the operator, SOC_{bat} is the battery state of charge, $\dot{H}$ is the rate of fuel consumption, P_{ICE} is the power supplied by the ICE (internal combustion engine), η is the inefficiency and c_{ICE} is the fuel coefficient.

$$\eta = \frac{1}{\text{efficiency}} = \frac{P_{in}}{P_{out}} \tag{4}$$

η will be strictly larger than 1 in a system with losses. The smaller η is, the less fuel is used to compensate for systemic inefficiencies.

$$P_{ICE} = P_{req} \cdot \eta_{SYS} \tag{5}$$

where system is the boundary from ICE output shaft to the work required by the operator (Figure 1).

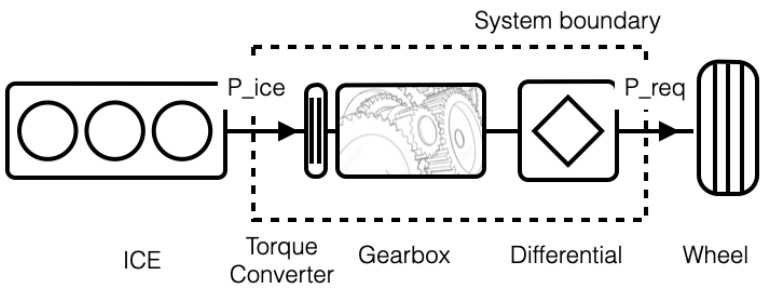


Figure 1: System boundary of the conventional drivetrain

© 2022 4QT Holding AG. All rights reserved.

In order to understand the efficiency gains of the Paris Hybrid^{TM} drivetrain in comparison to the state-of-the-art technology, a series hybrid system is used (Figure 2). Using (3) and (5):

$$\dot{H} = P_{req} \cdot \eta_{sys} \cdot \eta_{ICE} \cdot c_{ICE} \tag{6}$$

η_{SH} is the series hybrid and η_{4QT} is the Paris Hybrid^{TM} drivetrain efficiency.

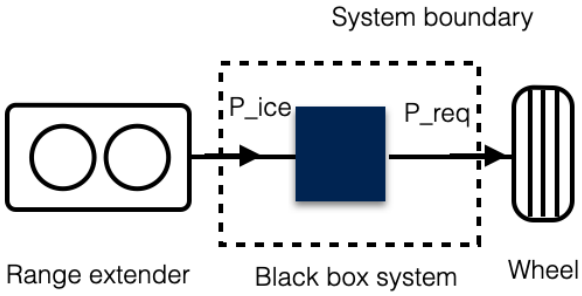


Figure 2: System boundary of a generic drivetrain

$$\dot{H}_{SH} = P_{req} \cdot \eta_{SH} \cdot \eta_{ICE} \cdot c_{ICE} \tag{7}$$

$$\dot{H}_{DRM} = P_{req} \cdot \eta_{4QT} \cdot \eta_{ICE} \cdot c_{ICE} \tag{8}$$

Relative rate of fuel consumption when switching to the DRM (Double Rotor Machine) from a series hybrid can be expressed as:

$$\dot{H}_{REL} = \frac{\dot{H}_{DRM} - \dot{H}_{SH}}{\dot{H}_{DRM}} \cdot 100 \tag{9}$$

Combining (8) and (9):

$$\dot{H}_{REL} = \frac{\eta_{4QT} - \eta_{SH}}{\eta_{4QT}} \cdot 100 = 1 - \frac{\eta_{SH}}{\eta_{4QT}} \cdot 100 \tag{10}$$

If the Paris Hybrid^{TM} drivetrain (Figure 4) is more efficient, one expects $\dot{H}_{REL}$ to be negative, showing the % fuel savings by the system.

© 2022 4QT Holding AG. All rights reserved.

5 Series Hybrid Drivetrain

The defined system boundary for the series hybrid is given in Figure 3.

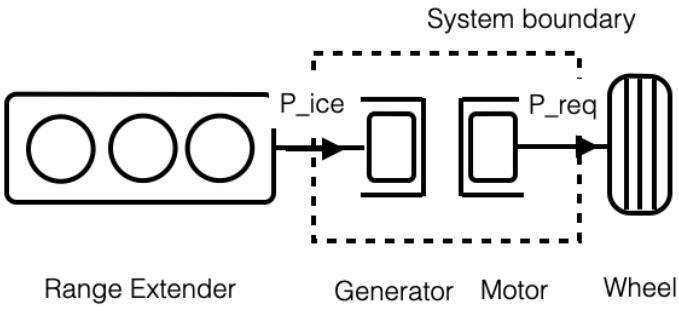


Figure 3: System boundary of the series hybrid

Now, η_{4QT} and η_{SH} are required to be derived.

$$P_{motor} = P_{req} \cdot \eta_{EL} \tag{11}$$

$$P_{generator} = P_{motor} \cdot \eta_{EL} \tag{12}$$

$$P_{ICE} = P_{generator} = P_{req} \cdot \eta_{EL}^2 \tag{13}$$

From (5) follows:

$$P_{ICE} = P_{req} \cdot \eta_{SH} \tag{14}$$

$$P_{req} \cdot \eta_{EL}^2 = P_{req} \cdot \eta_{SH} \tag{15}$$

$$\eta_{SH} = \eta_{EL}^2 \tag{16}$$

© 2022 4QT Holding AG. All rights reserved.

6 Paris Hybrid^{TM} Drivetrain

The defined system boundary for the Paris Hybrid^{TM} drivetrain is given in Figure 4.

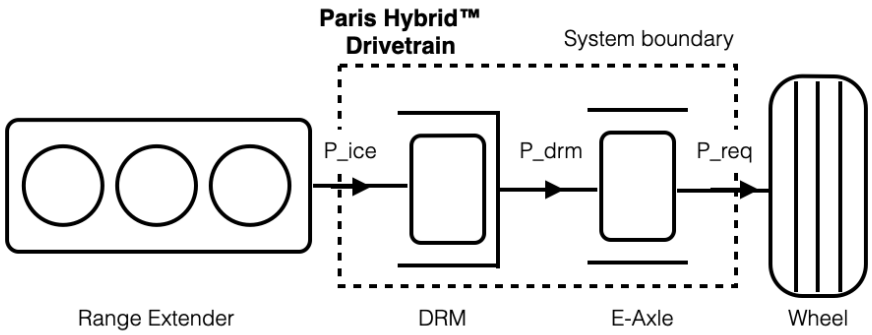


Figure 4: System boundary of the Paris Hybrid^{TM} drivetrain

Recalling that $P = \omega \cdot \tau$, one can write:

$$P_{req} = \omega_{req} \cdot \tau_{req} \tag{17}$$

$$P_{ICE} = \omega_{ICE} \cdot \tau_{ICE} \tag{18}$$

In order to keep everything neat, some variables are picked and to reformulate the equations to those variables. The variables of choice are all those in P_{req}, τ_{req}, P_{ICE} and τ_{ICE}.

In order to focus on one of the quadrants, $\omega_{ICE} > \omega_{req}$ is chosen. In this case, the DRM is in generator mode:

$$P_{generator-EL_{out}} = (\omega_{in} - \omega_{out}) \cdot \tau_{generator} \cdot \frac{1}{\eta_{EL}} \tag{19}$$

$$P_{DRM-EL_{out}} = (\omega_{DRM_{in}} - \omega_{DRM_{out}}) \cdot \tau_{DRM_{in}} \cdot \frac{1}{\eta_{EL}} \tag{20}$$

© 2022 4QT Holding AG. All rights reserved.

There are two independent axes and thus two angular speeds in the system:

$$\omega_{req} = \omega_{eAXLE} = \omega_{DRM_{out}} \tag{21}$$

$$\omega_{ICE} = \omega_{DRM_{in}} \tag{22}$$

$$\tau_{ICE} = -\tau_{DRM_{in}} \tag{23}$$

Inserting (21), (22) and (23) in (20)

$$P_{DRM-EL_{out}} = P_{DRM} = -(\omega_{ICE} - \omega_{req}) \cdot \tau_{ICE} \cdot \frac{1}{\eta_{EL}} \tag{24}$$

The terms are to be simplified to the variables of choice.

A word about the ratio of the losses and the sign of the term. With $\omega_{ICE} > \omega_{req}$, a negative P_{DRM} signifies the kinetic power converted to electric power. In steady state, this is fed back into the e-Axle. In dynamic conditions, the battery is charged.

$$P_{eAXLE} = -P_{DRM} \cdot \frac{1}{\eta_{EL}} \tag{25}$$

Combining (24) and (25):

$$P_{eAXLE} = (\omega_{ICE} - \omega_{req}) \cdot \tau_{ICE} \cdot \frac{1}{\eta_{EL}^2} \tag{26}$$

Recall that $\eta_{EL} = 1/losses$, or the factor needed to compensate for losses in the drivetrain down the line. The only thing missing and incidentally the point of this proof is the power transmitted because of the reactive torque of the DRM.

Following from Newton's 3^{rd} law of motion:

$$\tau_{DRM_{in}} = -\tau_{DRM_{out}} \tag{27}$$

© 2022 4QT Holding AG. All rights reserved.

Hence (27) yields:

$$P_{DRM_{newton}} = \tau_{DRM_{out}} \cdot \omega_{DRM_{out}} \tag{28}$$

Using (21), (23) and (27), one can rewrite (28) with the variables of choice:

$$P_{DRM_{newton}} = \tau_{ICE} \cdot \omega_{req} \tag{29}$$

This term is lossless. This is quite right and follows from the stated assumptions. The reason is that it is a reaction to the torque resulting from transforming energy from kinetic into electric form as described in (24). Newton's law does not foresee a smaller reactive force or torque, but an equally strong force or torque with different sign.

P_{req} can then be expressed as:

$$P_{req} = P_{DRM_{newton}} + P_{eAXLE} \tag{30}$$

Expanding (30) by using (29) and (26) yields:

$$P_{req} = \tau_{ICE} \cdot \omega_{req} + (\omega_{ICE} - \omega_{req}) \cdot \tau_{ICE} \cdot \frac{1}{\eta_{EL}^2} \tag{31}$$

As for the series hybrid, the generic from in (5) can be written to the specific DRM form:

$$P_{ICE} = P_{req} \cdot \eta_{4QT} \tag{32}$$

or

$$P_{req} = \frac{P_{ICE}}{\eta_{4QT}} \tag{33}$$

© 2022 4QT Holding AG. All rights reserved.

Using (31) with (33) yields:

$$\frac{P_{ICE}}{\eta_{4QT}} = \tau_{ICE} \cdot \omega_{req} + (\omega_{ICE} - \omega_{req}) \cdot \tau_{ICE} \cdot \frac{1}{\eta_{EL}^2} \tag{34}$$

Solving for η_{4QT} one can write (34) as:

$$\eta_{4QT} = \frac{1}{\frac{\omega_{req}}{\omega_{ICE}} \cdot \left(1 - \frac{1}{\eta_{EL}^2}\right) + \frac{1}{\eta_{EL}^2}} \tag{35}$$

When $\omega_{req} = 0 \Rightarrow \eta_{4QT} = \eta_{EL}^2 = \eta_{SH}$

When $\omega_{req} \Rightarrow \omega_{ICE} \Rightarrow \eta_{4QT} \Rightarrow 1$ while $\eta_{SH} = \eta_{EL}^2$

For all $\omega_{req} > 0$ and $\omega_{req} < \omega_{ICE}$ the DRM is more efficient than the series hybrid. This can also be shown for the other operating quadrants.

7 Relative Fuel Savings of Paris Hybrid™ Drivetrain

Coming back to (10), it can now be written as:

$$\dot{H}_{REL} = \left[1 - \frac{\eta_{EL}^2}{\frac{1}{\frac{\omega_{req}}{\omega_{ICE}} \cdot \left(1 - \frac{1}{\eta_{EL}^2}\right) + \frac{1}{\eta_{EL}^2}}}\right] \cdot 100 \tag{36}$$

$$\dot{H}_{REL} = \left[1 - \left(\frac{\omega_{req}}{\omega_{ICE}} \cdot (\eta_{EL}^2 + 1) - 1\right)\right] \cdot 100 \tag{37}$$

$$\dot{H}_{REL} = \left[\frac{\omega_{req}}{\omega_{ICE}} \cdot (1 - \eta_{EL}^2)\right] \cdot 100 \tag{38}$$

when $\omega_{req} = 0 \Rightarrow \dot{H}_{REL} = 0$

when $\omega_{req} = \omega_{ICE} \Rightarrow \dot{H}_{REL} = (1 - \eta_{EL}^2) \cdot 100$

© 2022 4QT Holding AG. All rights reserved.

Assuming the efficiency of electric machines plus power electronics to be around 85%. Then $\eta_{EL} = 1.38$ and:

when $\omega_{req} \Rightarrow 0.7 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -27\%$

when $\omega_{req} \Rightarrow 0.8 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -30\%$

when $\omega_{req} \Rightarrow 0.9 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -35\%$

when $\omega_{req} \Rightarrow 1.0 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -38\%$

Assuming the efficiency of electric machines plus power electronics to be around 80%. Then $\eta_{EL} = 1.56$ and:

when $\omega_{req} \Rightarrow 0.7 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -39\%$

when $\omega_{req} \Rightarrow 0.8 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -45\%$

when $\omega_{req} \Rightarrow 0.9 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -50\%$

when $\omega_{req} \Rightarrow 1.0 \cdot \omega_{ICE} \Rightarrow \dot{H}_{REL} = -56\%$

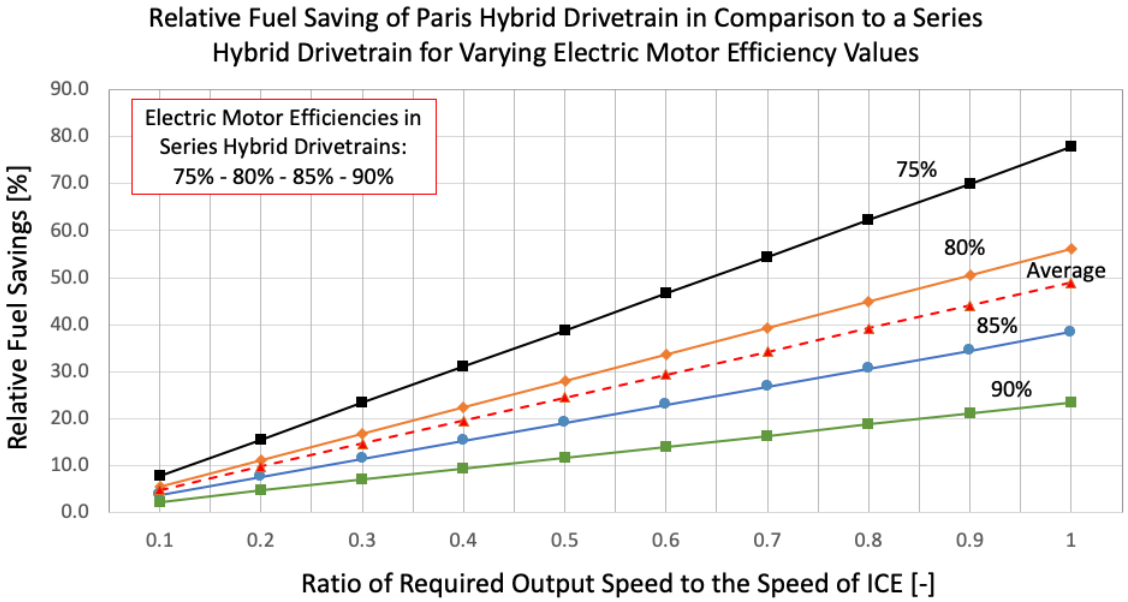


Figure 5: Relative Fuel Saving of Paris Hybrid Drivetrain in Comparison to a Series Hybrid Drivetrain for Varying Electric Motor Efficiency Values

© 2022 4QT Holding AG. All rights reserved.

8 Conclusion

At speeds above $0.7 \cdot \omega_{ICE}$ and for an electric machine efficiency of 85% in a series hybrid, the ParisHybrid^{TM} drivetrain from 4QT Holdings AG achieves at least -27% fuel and carbon use compared to a high efficiency series hybrid system. In the case of a medium efficiency series hybrid system (75%), the ParisHybrid^{TM} drivetrain achieves up to -56% fuel and carbon use.

© 2022 4QT Holding AG. All rights reserved.