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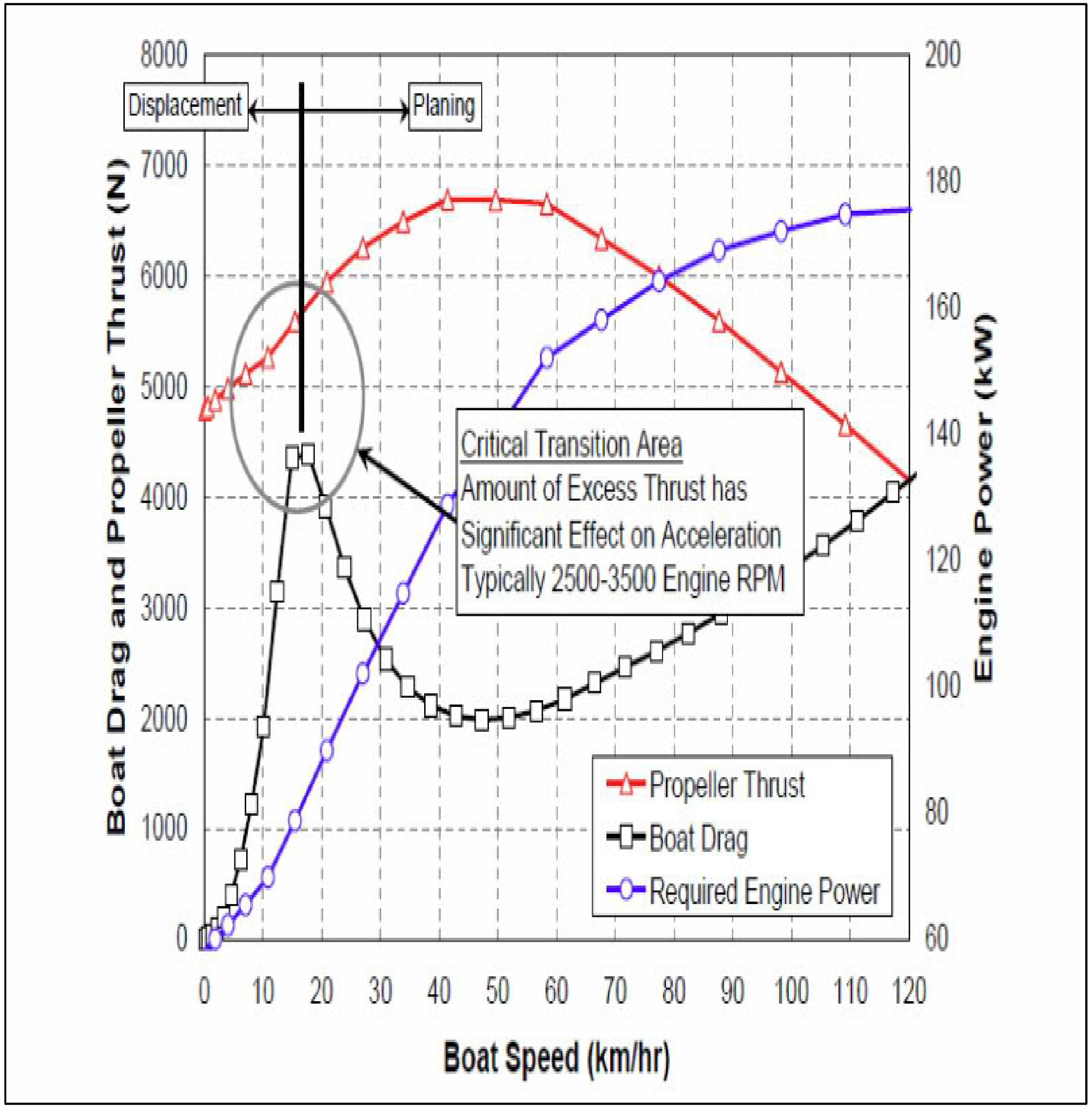
TURBOCHARGHED DIESEL ENGINE COUPLED WITH PLANING VESSEL

Ricardo Software 2015 European User Conference

Prof. Giovanni Ferrara - Giovanni Vichi - **Pietro Bianchi**

Field of research

- Engines for planing boats
  - ✓ **Marine turbocharged Medium Duty diesel engines**
    - Matching of engine - propeller - hull
  - ✓ **Two competing requirements:**
    - High power density in order to reach high peak velocity;
    - Low End Torque Availability to overcome the peak of resistance in the displacement to planing transition phase.



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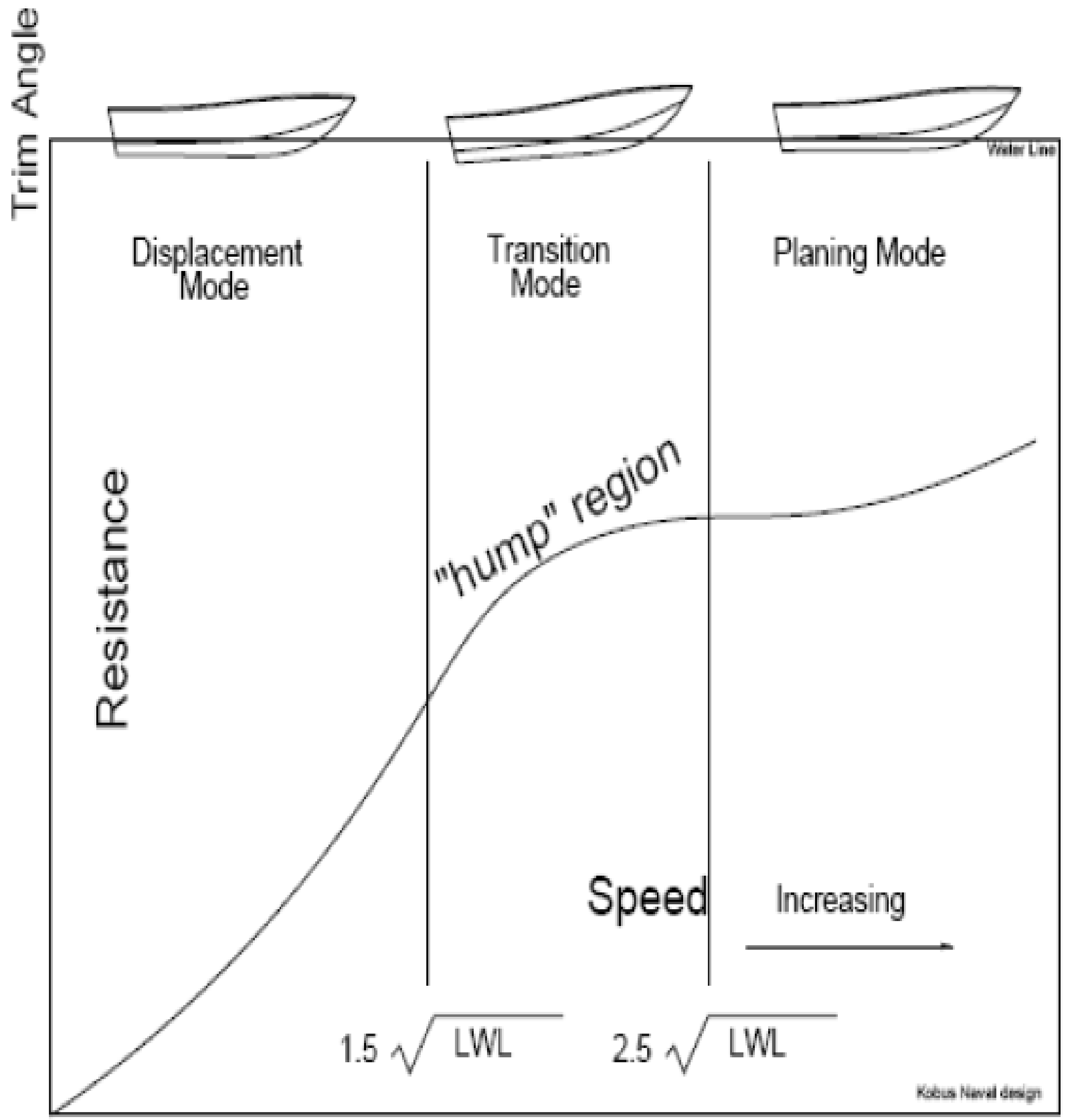
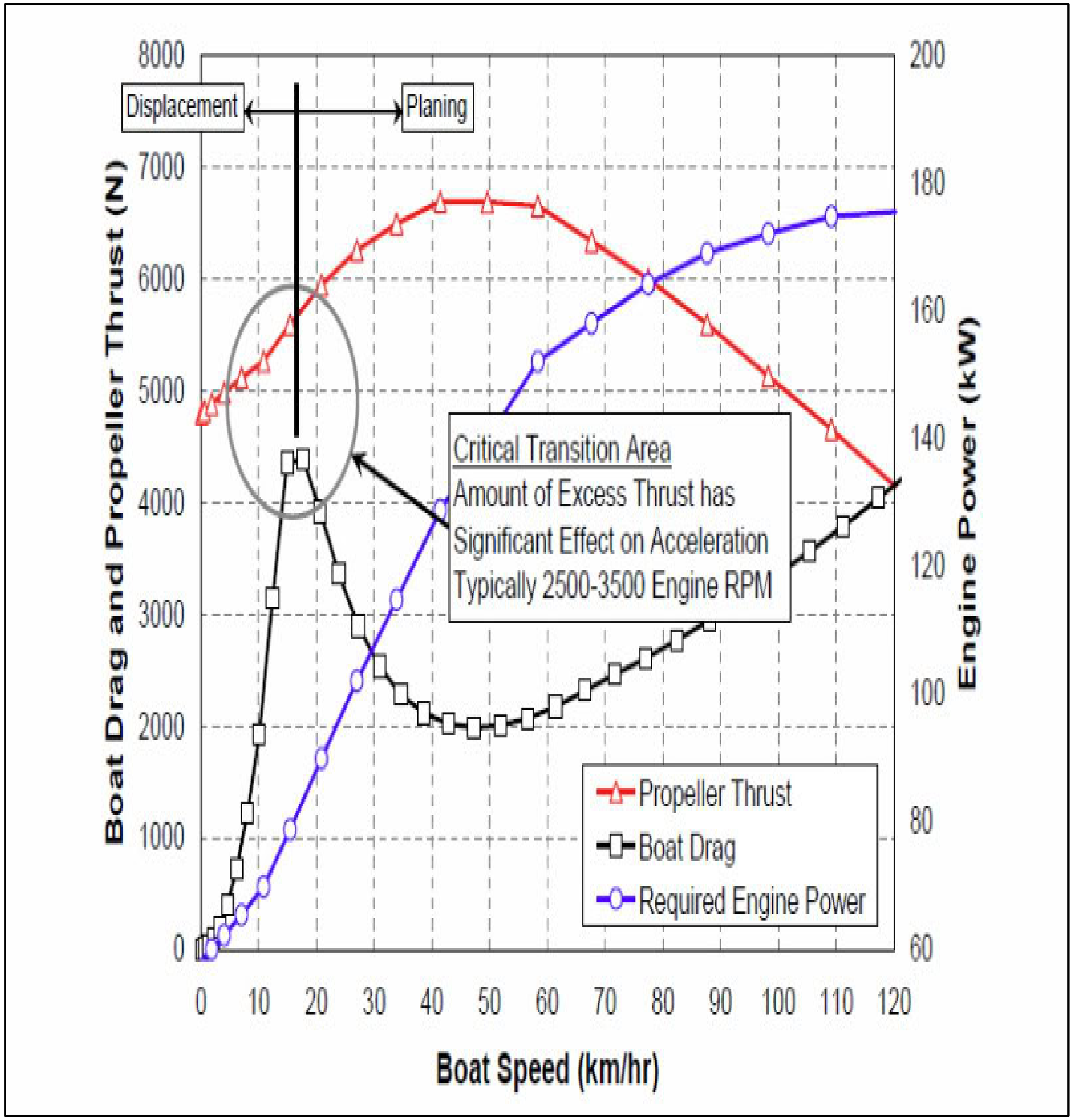
Framework: Boat Displacement to Planing transition

- **Resistance to the motion of the planing boat:**
  - ✓ *Displacement condition*
    - o The resistance grows with the velocity up to the *critical transition velocity*
  - ✓ *Planing condition*
    - o The hull shape allows the partial raising of the boat on the water
      - Hydrodynamic reaction
      - Reduction of the viscous force (reduction of the wet surface)
      - Strong reduction of the residual resistance (wave resistance + vortices)
      - The total resistance gradually grows up to the maximum velocity



Engine Matching to Transmission

- Turbocharger Matching to boat:
  - <u>Surplus of power after transition:</u>
    - Standard solution
      - *Dual gear transmission*
      - *Variable pitch propellers*
    - Innovative solutions
      - *Electrical or mechanical charger in series with the turbocharger*
      - *MGU Turbocharger*
        - No turbo-lag and overpressure air immediately available to the engine even at low rpm
        - It is possible to use the turbocharger to recover the surplus energy when the peak of resistance is overtaken
        - The surplus energy used for the subsequent acceleration or for the auxiliary equipment



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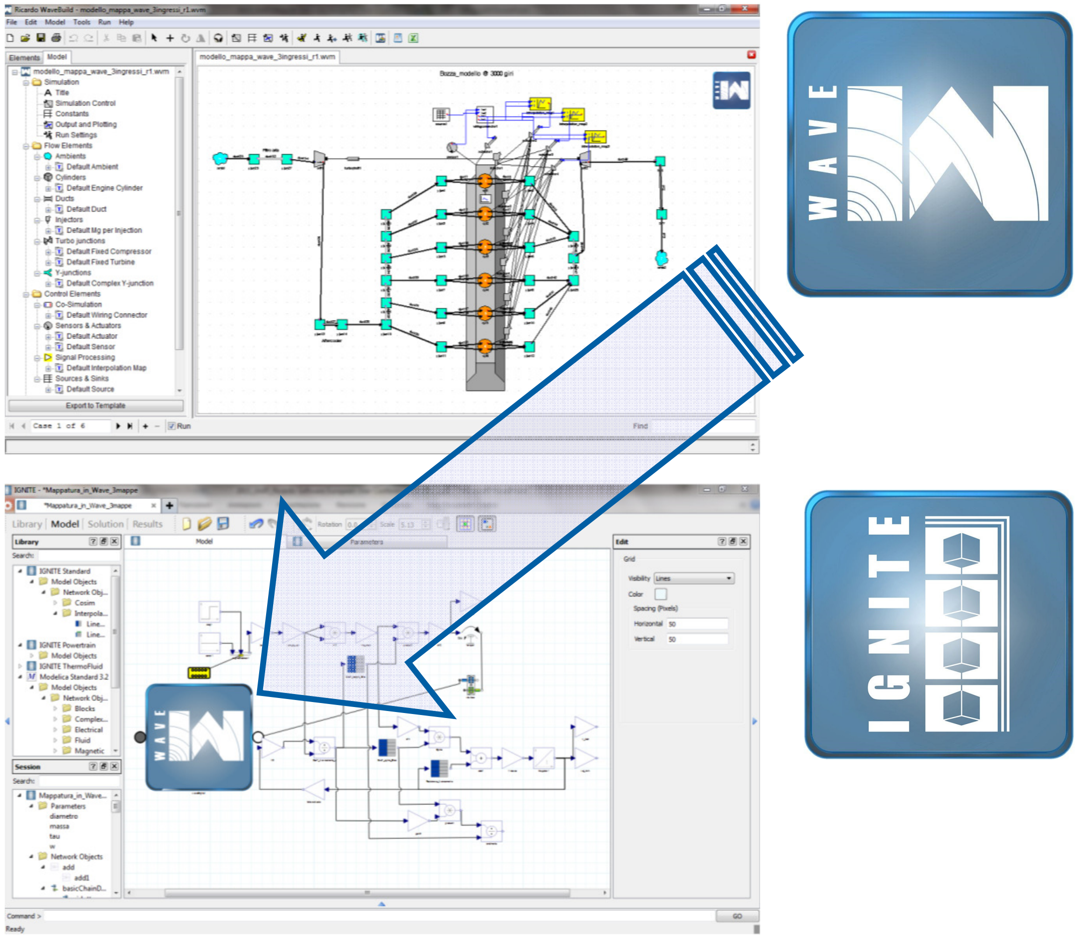
Aim of the activity:
Provide a simulation tool for planing boat transmission dynamics

- ✓ Development of an *engine-transmission-boat* numerical model:
  - *Goal*:
    - evaluate during the design phase if the **engine-turbocharger matching** is able to guarantee both **high power** and **low end torque to start "planing"**
  - *Numerical Tools*:
    - 1D engine model built in **Wave**
    - Mathematical model to simulate the longitudinal dynamic of the boat implemented in **IGNITE**
    - Integration of the engine model with the boat model:
  - *Future development:*
    - evaluate the coupling among engine – MGU Turbocharger, operating also in energy recovery mode.



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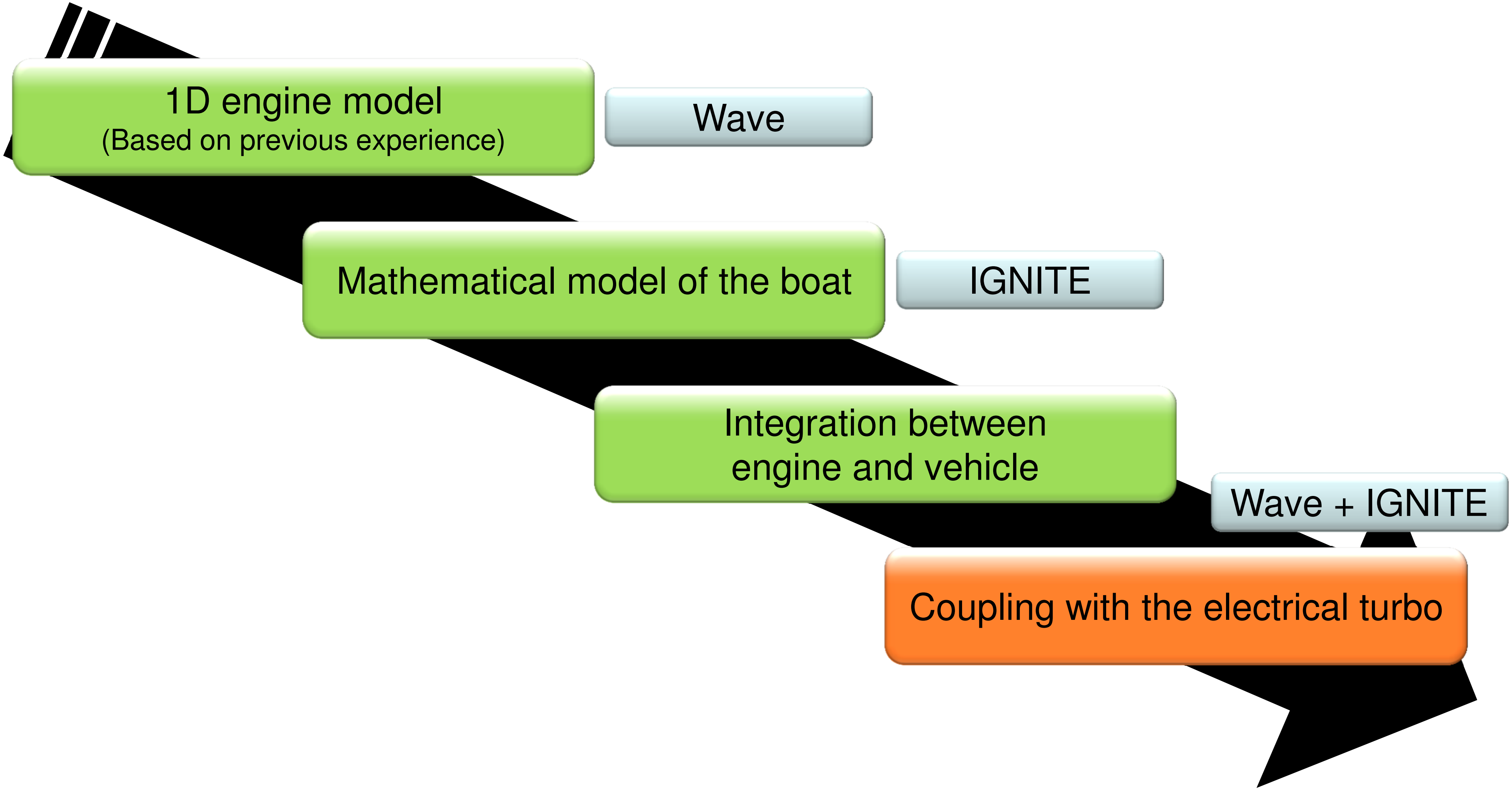
Road Map



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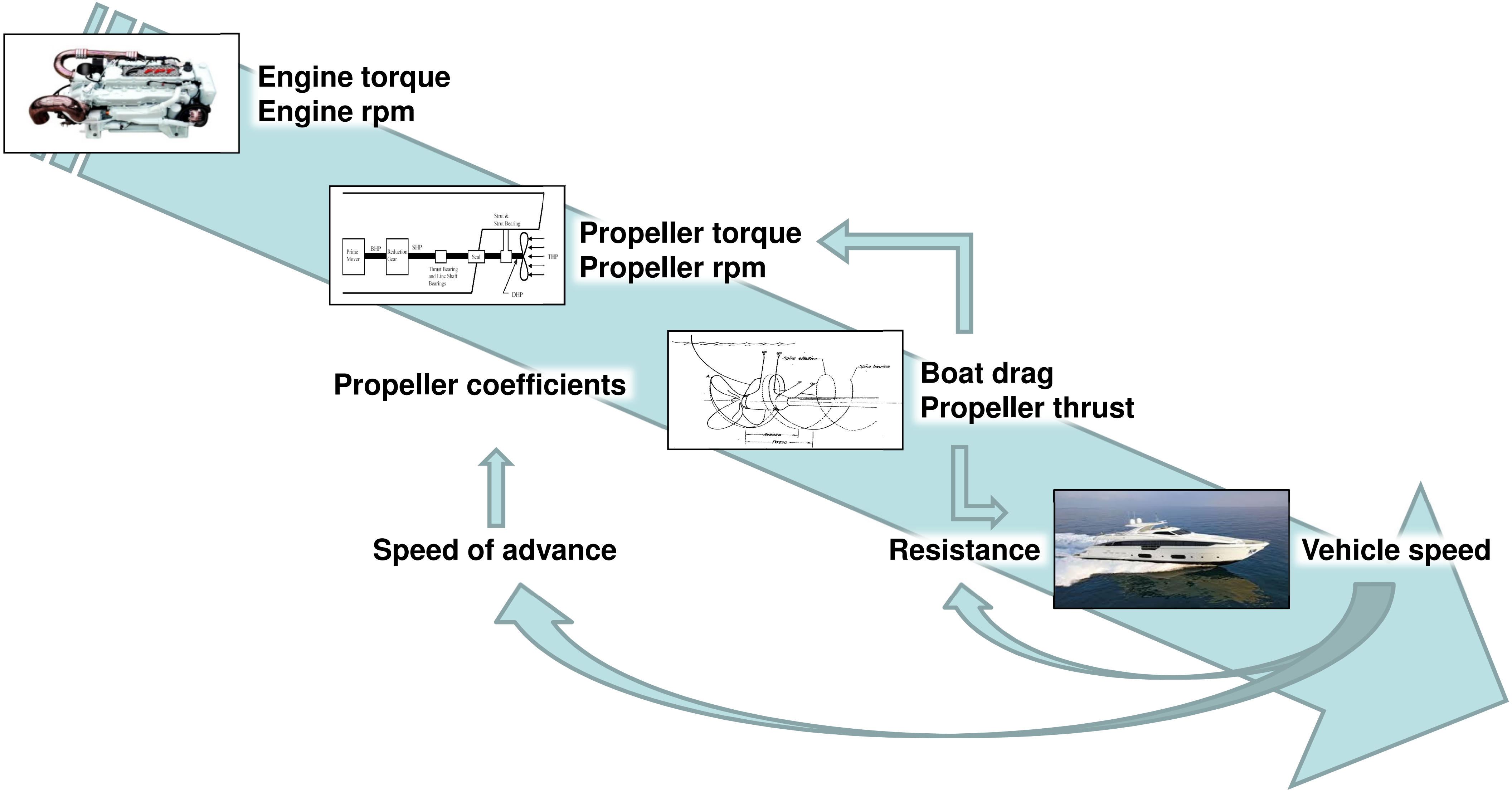
Boat dynamic



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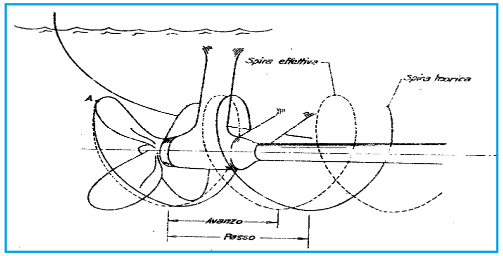
Boat dynamic – mathematical model



PROPELLER

- Simplest Propeller Model:
  - ✓ only thrust to the hull transmitted to boat
  - ✓ Immersed free propeller
    - Characteristics independent from the trim of the boat (e.g. from the flotation or boat pitch angle)
    - Characteristic parameters of the propellers
      - Grouped by reference series
        - » Number of blades
        - » Pitch / Diameter Ratio
        - » Projected blade area / Disc area Ratio

Ref.: Guidance and control of ocean vehicles, T. Fossen

Ref.: Nozioni di macchine marine, Accademia Navale

Ref.: Fondamenti di Idrodinamica, U. Costaguta

Ref.: Marine propellers and propulsion, J. Carlton

Ref.: The prediction of power performance of planing crafts, J.B. Hadler, SNAME, 1966

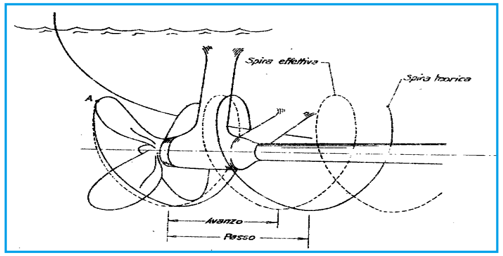
Ref.: Fondamenti e applicazioni di propulsione navale, G. Trincas, Università di Trieste

Ref.: Lo scafo da diporto, A. Payer, M. Vassalle

Ref.: Le turbomacchine, G. Manfrida, S. Stecco

Ref.: Meccatronica, Elementi di trazione elettrica, B. Allotta, L. Pugi

Boat dynamic – mathematical model



PROPELLER

- Performance of the propeller from experimental tests in open-water available in literature

- *Advance coefficient* $$J = \frac{v_a}{n\,d}$$
- *Thrust coefficient* $$K_T = \frac{T}{\rho\, n^2 d^4}$$
- *Torque coefficient* $$K_Q = \frac{Q}{\rho\, n^2 d^5}$$

- v_a Propeller's speed of advance
- n Propeller's rotational speed
- d Propeller's diameter
- ρ Water density
- T Thrust
- Q Propeller's torque

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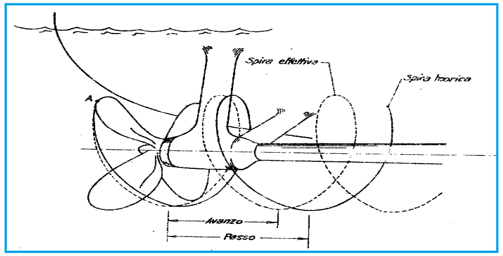
Boat dynamic – mathematical model

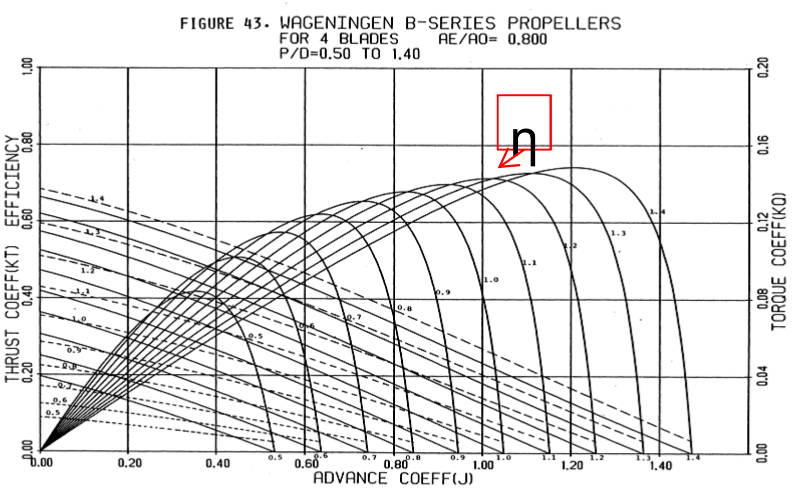


PROPELLER

- Propeller efficiency (η)
  - ✓ Function of the propeller coefficients

$$\eta = \frac{T v_a}{2\pi n Q} = \frac{P_T}{P_D} = \frac{K_T \rho n^2 d^4 v_a}{2\pi K_Q \rho n^3 d^5} = \frac{K_T v_a}{K_Q 2\pi n d} = \frac{K_T J}{2\pi K_Q}$$

  - ○ P_T : Thrust power of the propeller
  - ○ P_D : Power absorbed by the propeller behind the hull



K_T (J) → continuous line
K_Q (J) → dashed line

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Boat dynamic – mathematical model

➢ Thrust T is function of the variation of the axial component of the flow velocity
  ✓ The flow acceleration due to the enthalpy drop Δh at the propeller

➢ Once defined the propeller characteristics
  ✓ Thrust: $T = K_T \rho n^2 d^4$
  ✓ Propeller's torque: $Q = K_Q \rho n^2 d^5$

PROPELLER

BOAT

- Thrust T is function of the variation of the axial component of the flow velocity
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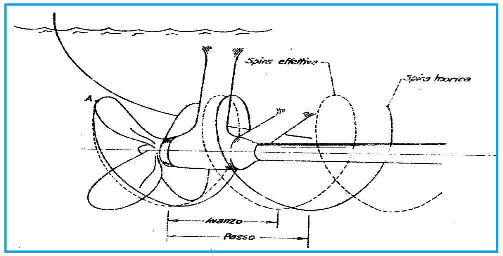
Boat dynamic – mathematical model



PROPELLER

BOAT

- v_a → relative water velocity behind the hull considering a reference system fixed to the boat
- Compared to the open-water condition the propeller works in a disturbed flow
  - ✓ The water around the aft assumes an advancement motion in the same direction of the ship
    - Wake field
  - ✓ Wake velocity → $v_w = v - v_a$
    - v → boat speed
  - ✓ Taylor wake factor w
    - $w = \frac{v - v_a}{v} = 1 - \frac{v_a}{v}$
    - $v_w = wv$ → $v - v_a = wv$ → $v_a = v(1 - w)$
  - ✓ v_a is needed to estimate the dimensionless coefficients of the propeller

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Boat dynamic – mathematical model

BOAT

- Newton's second law in longitudinal direction
  - ✓ $T = T_x$
  - ✓ The resistance to the motion R
  - ✓ m = boat mass
    - Acceleration profile
    - Velocity profile

$$\sum F = ma \;\Rightarrow\; T - R = ma \;\Rightarrow\; v = \frac{1}{m}\int (T - R)$$

Ref.: K. Matveev, Modeling of longitudinal motions of a hydroplane boat, 2012
Ref.: Hydrocomp techinical report, Analysis of vessel acceleration with NavCad, 2003

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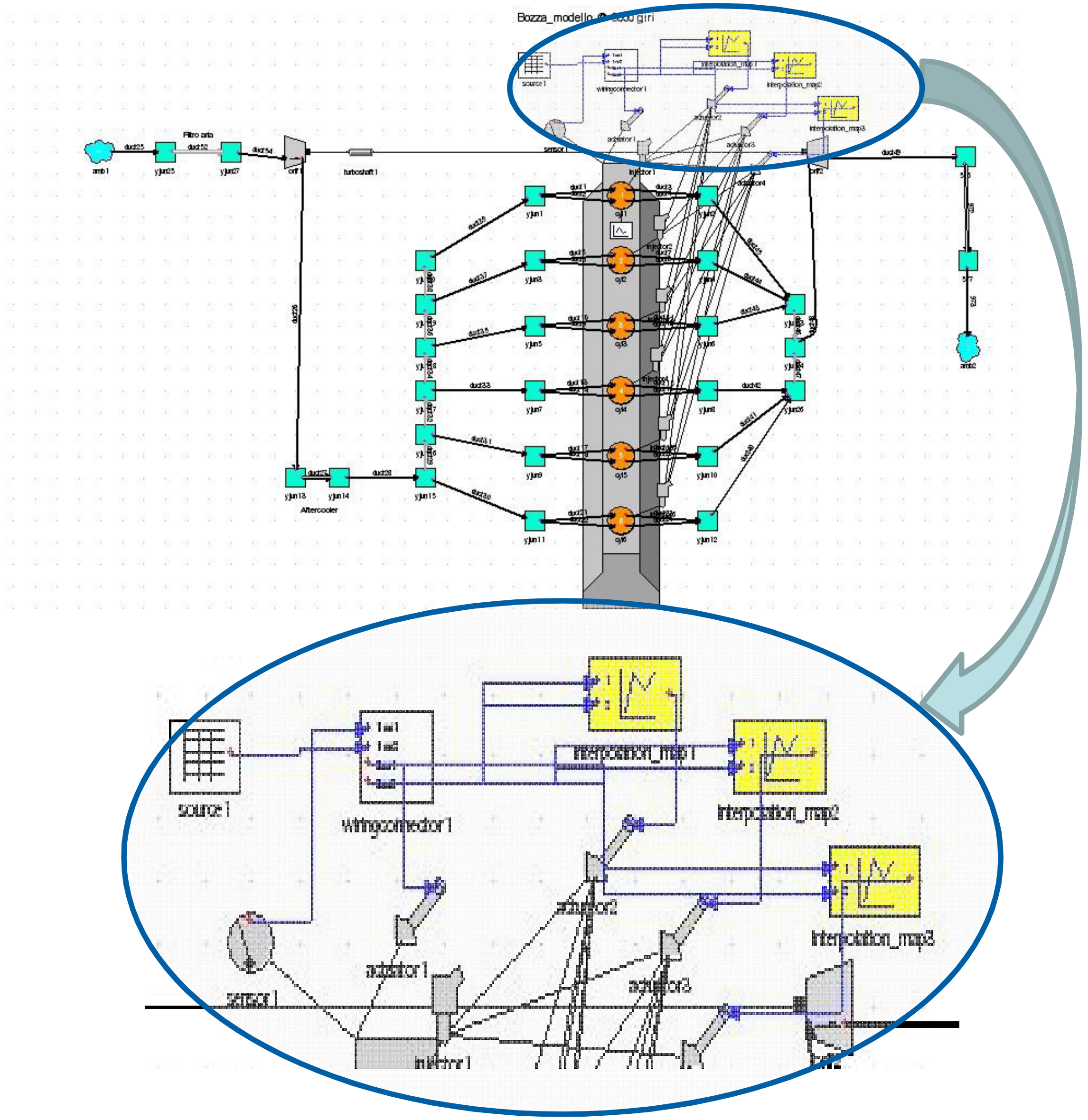
Coupling engine model – boat model

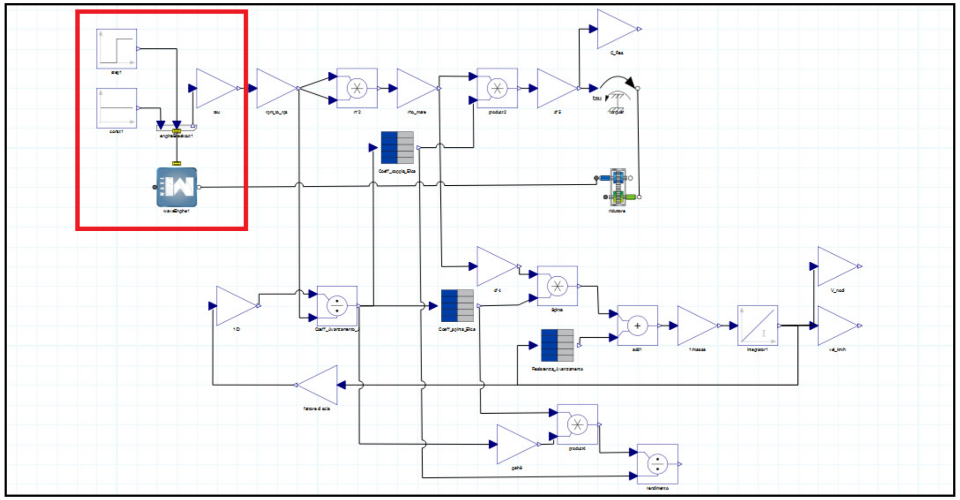
- Model with engine governor maps defined into Wave
  - ✓ Maps function of rpm and load
    - Fuel mass
    - Injection time
    - Start of injection
  - ✓ Wave ↔ IGNITE through Wiring-Connector
    - Wave input:
      - ✓ Engine rpm
      - ✓ Engine load
    - Wave output:
      - ✓ Torque [Nm]
      - ✓ Consumption [kg/h]
      - » ….

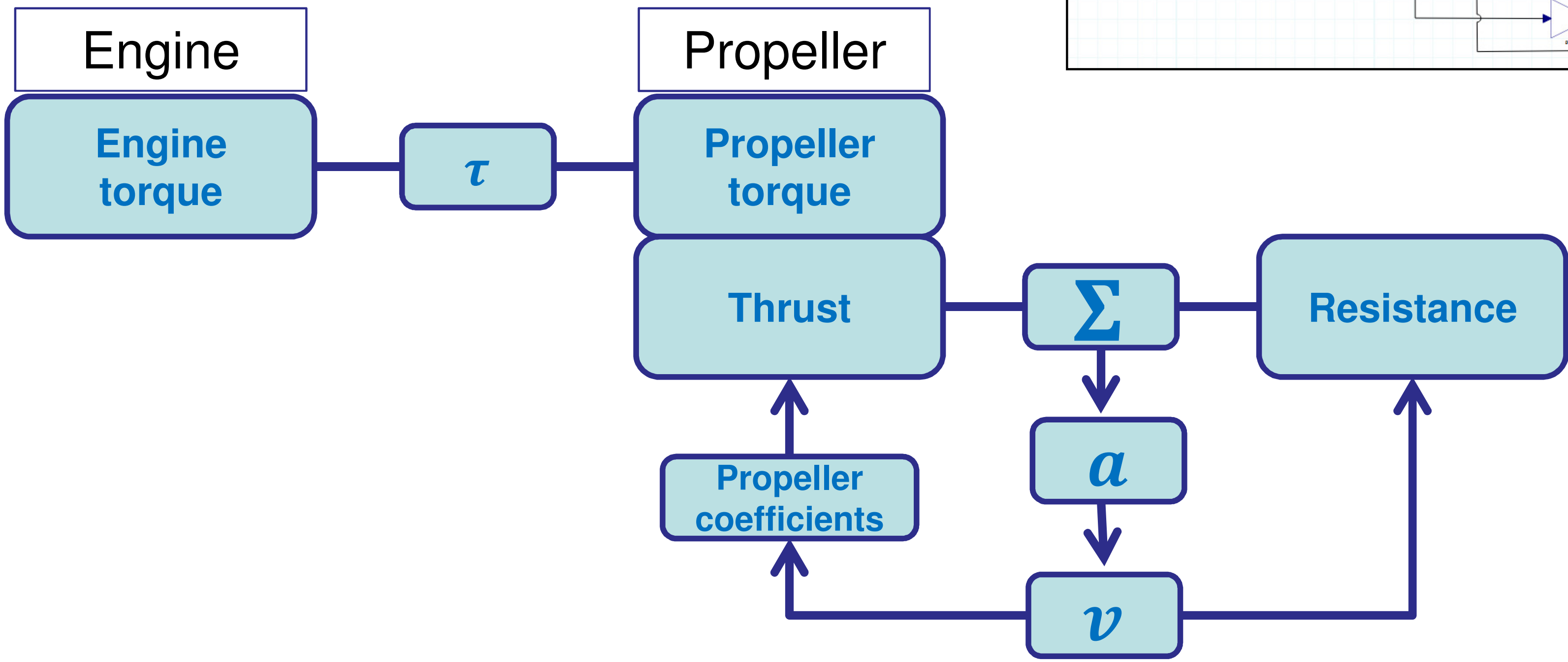


Further improvement: Wave RT implementation

Coupling engine model – boat model

- Engine torque
  - ✓ Load demand profile imposed
    - Step between minimum and maximum load





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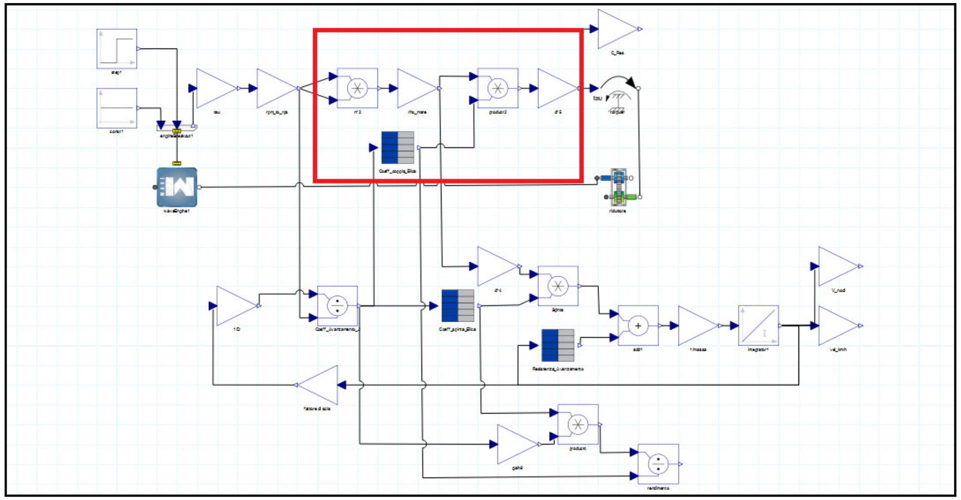
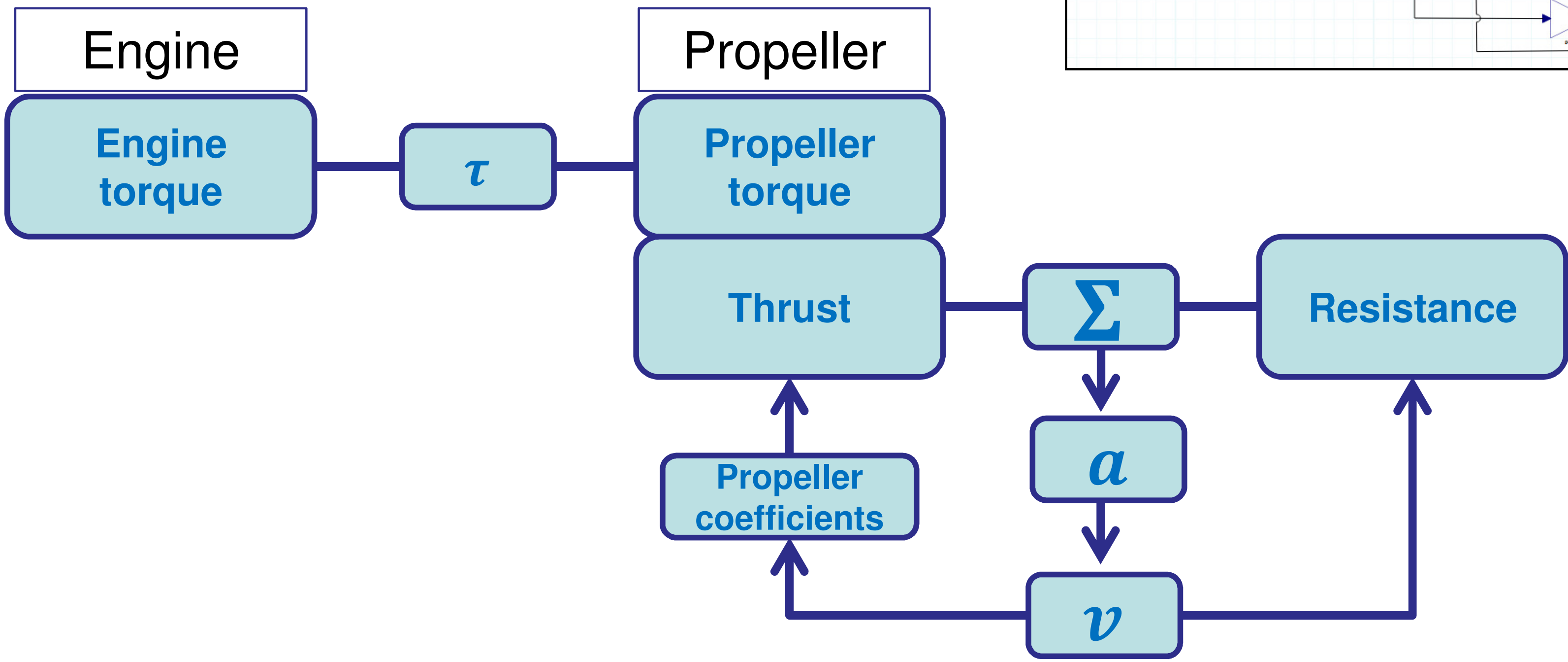
Coupling engine model – boat model

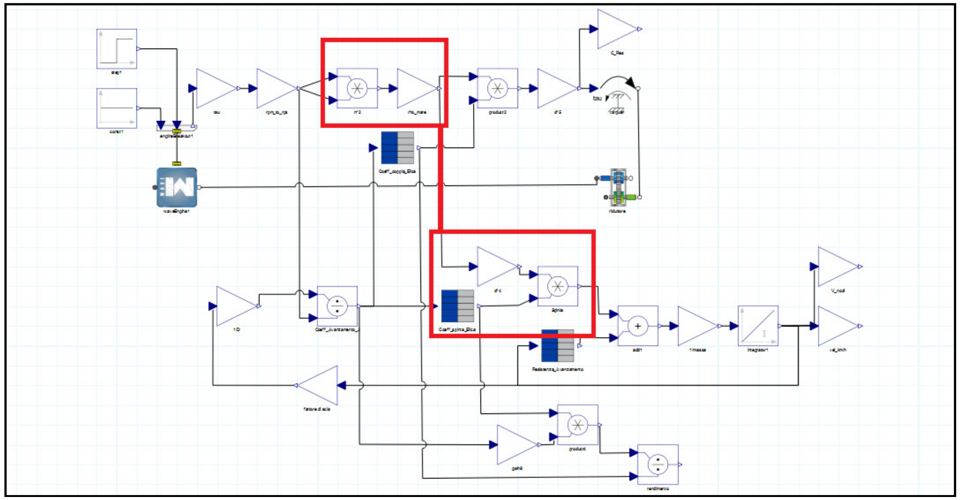
- Propeller torque
  - ✓ $Q = K_Q \rho n^2 d^5$
  - ✓ Interpolation table of K_Q(J)

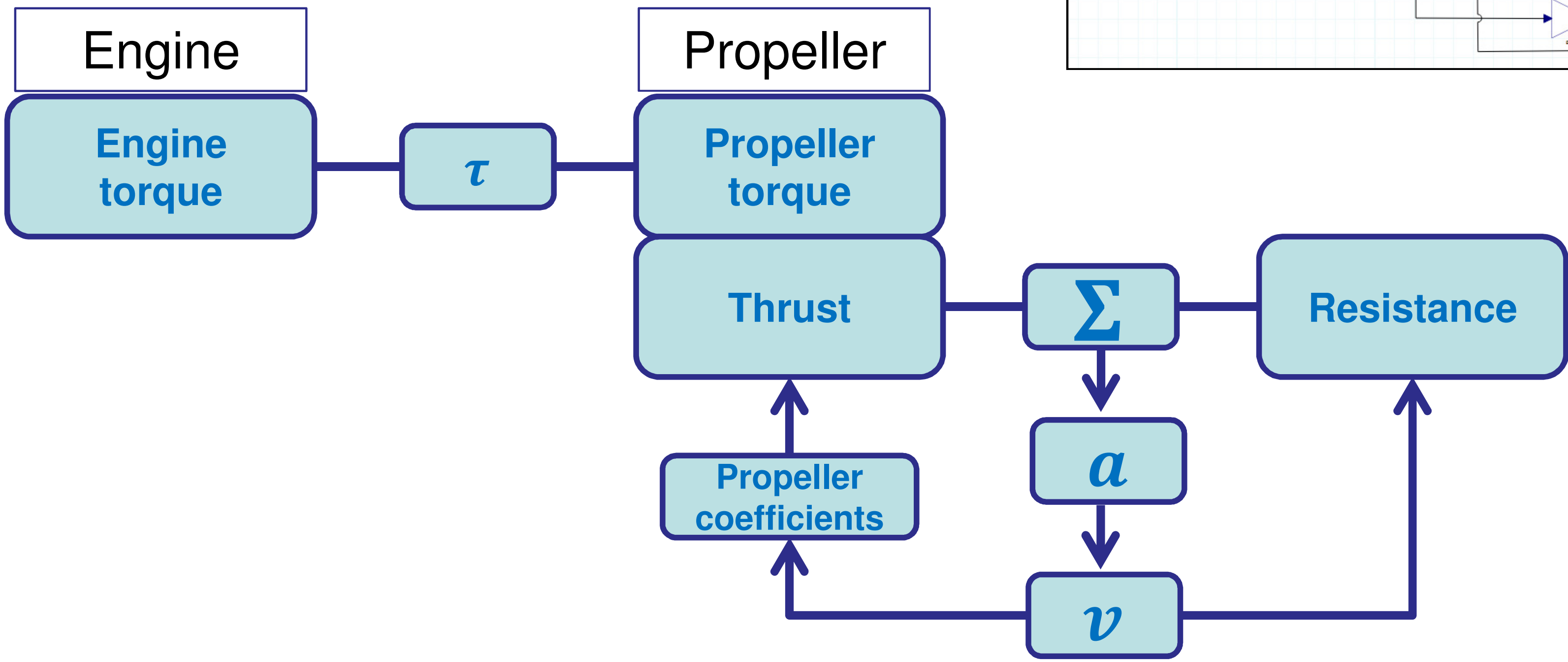




Coupling engine model – boat model

- Thrust
  - ✓ $T = K_T \rho n^2 d^4$
  - ✓ Interpolation table of $K_T(J)$





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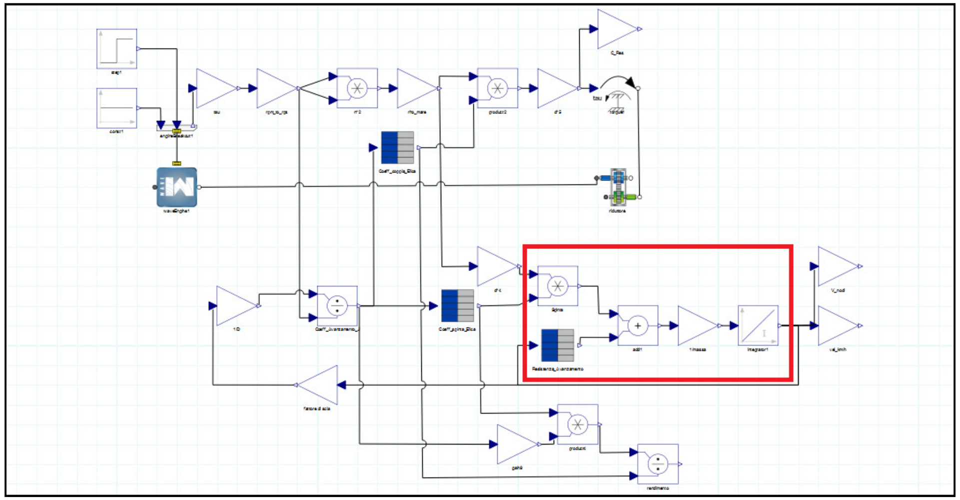
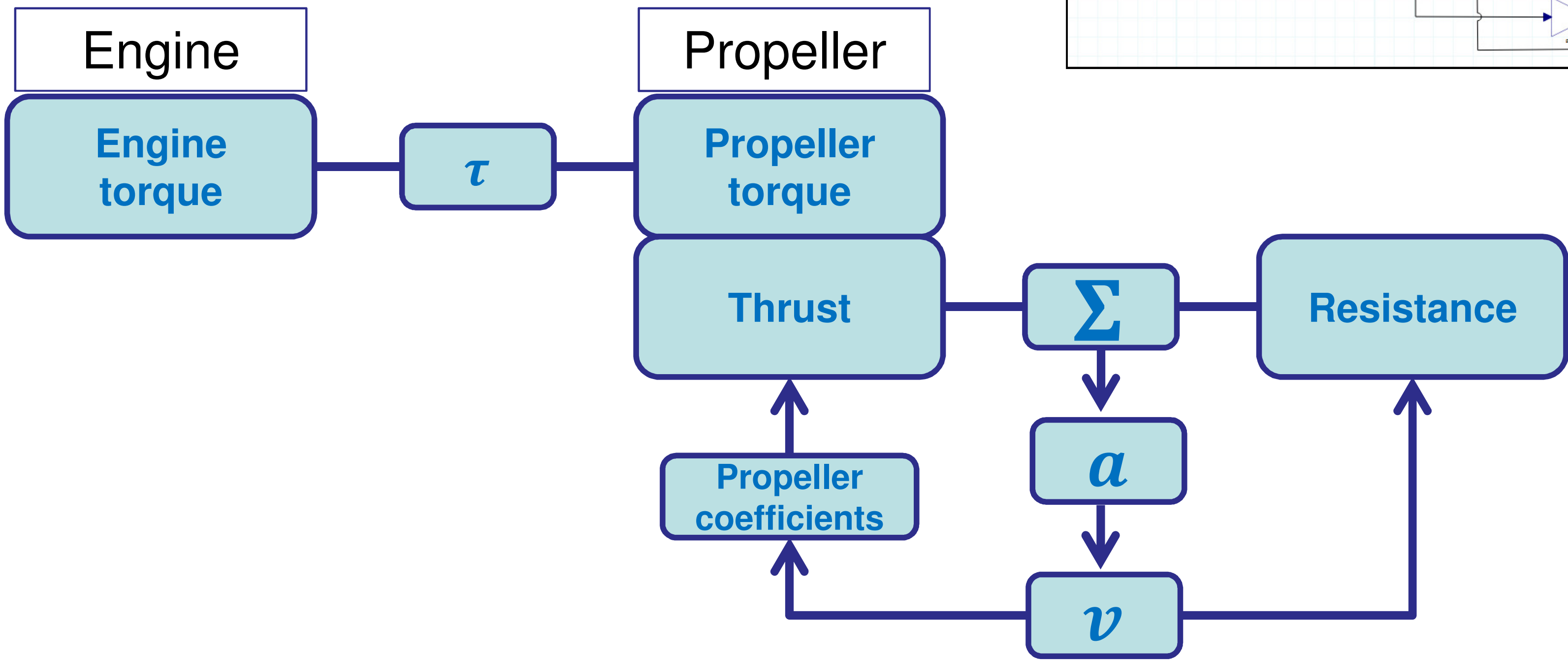
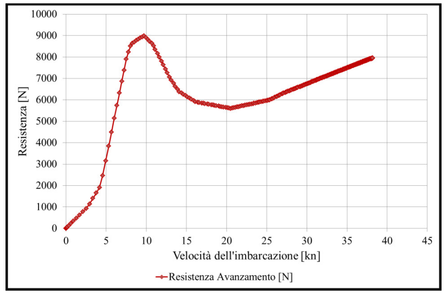
Coupling engine model – boat model

- Balance between thrust and resistance

$$v = \frac{1}{m} \int (T - R)$$







Imposed in the model

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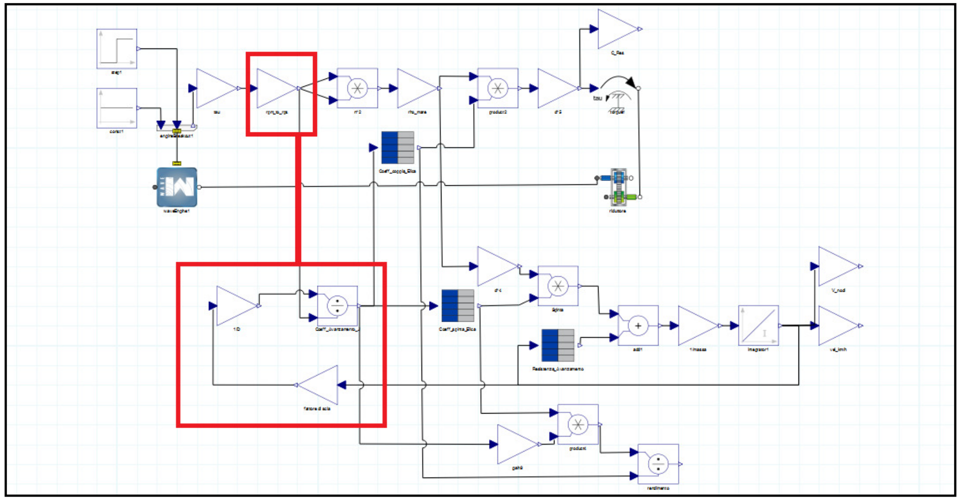
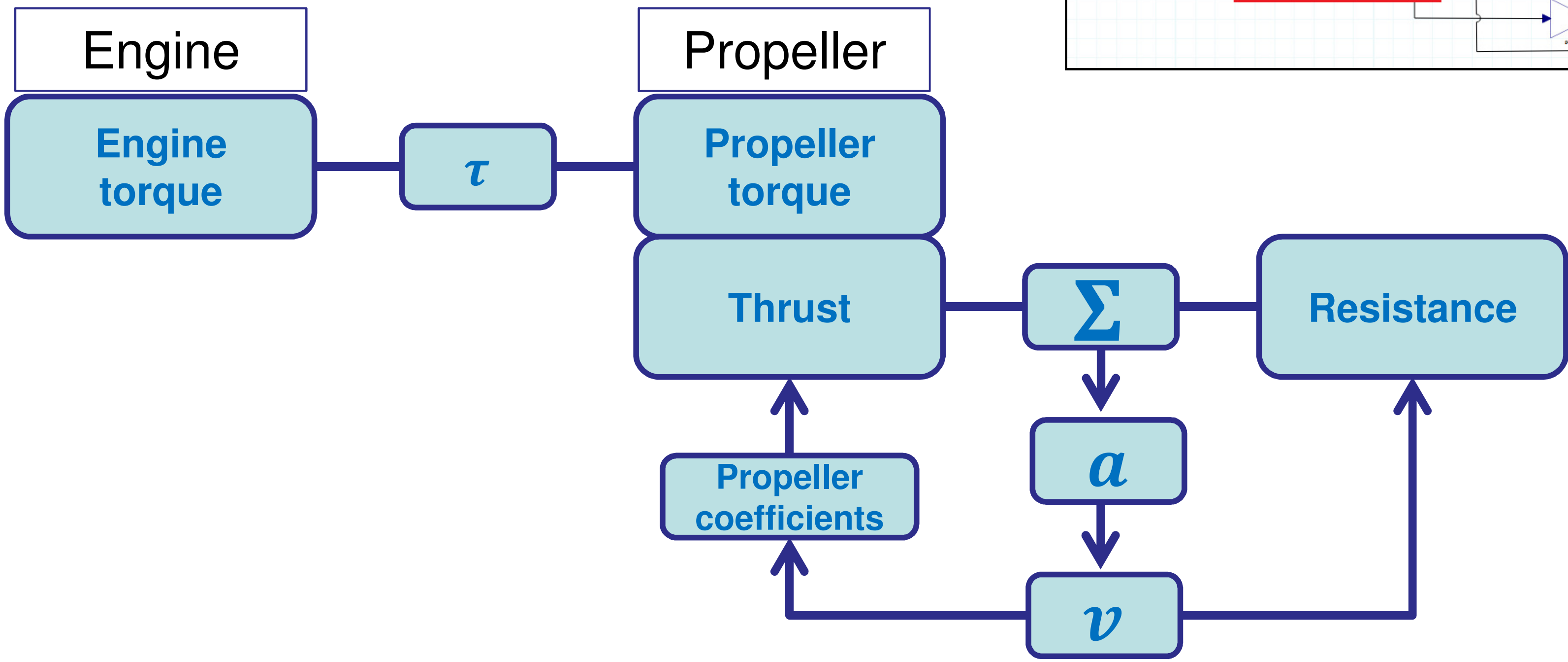
Coupling engine model – boat model

- Velocity v_a
- Advance coefficient J





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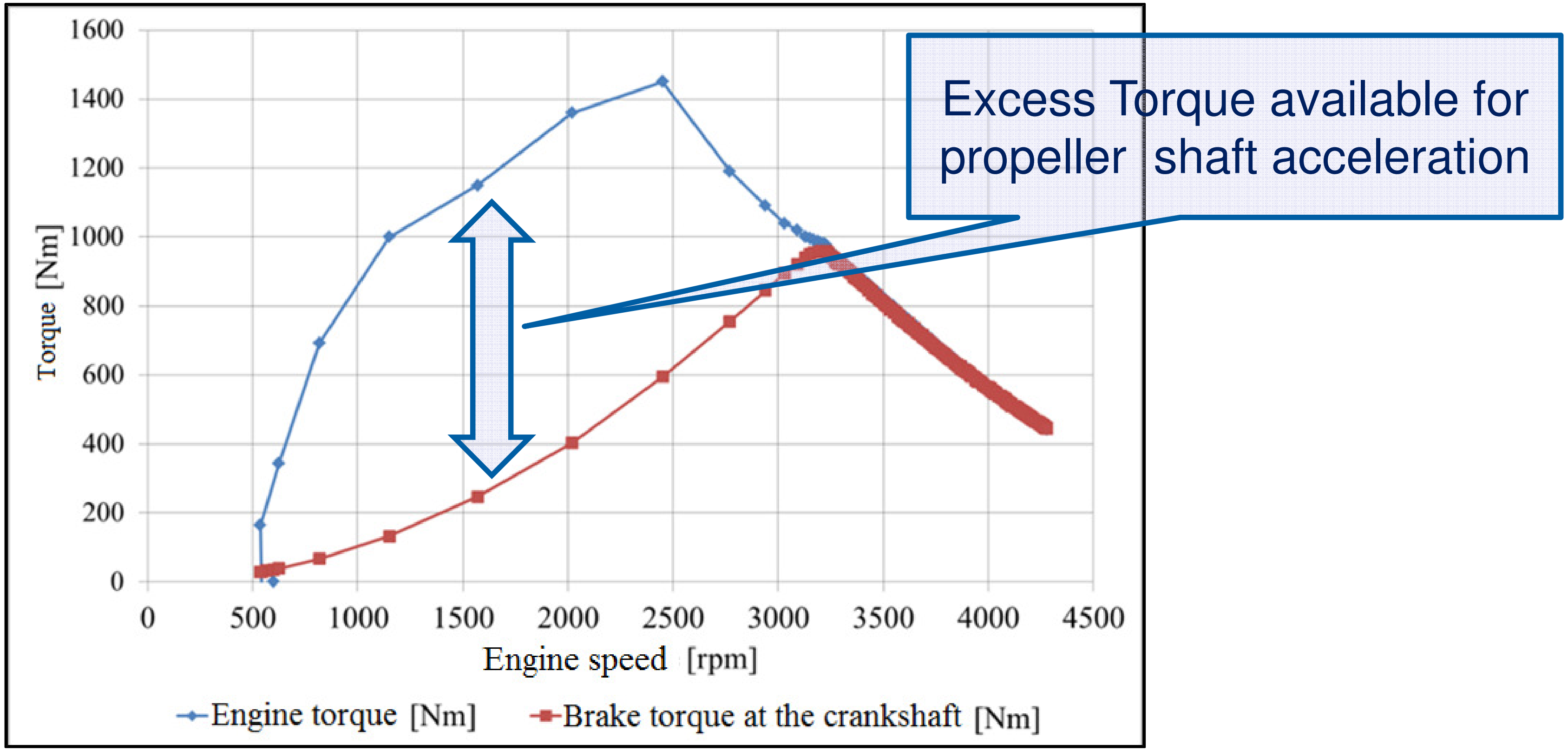
Results

- Engine torque and Brake torque at the crankshaft in function of the engine speed
  - ✓ Imposed an abrupt requested of torque from the minimum to the full load
  - ✓ Analysis of the maximum acceleration of the planing boat



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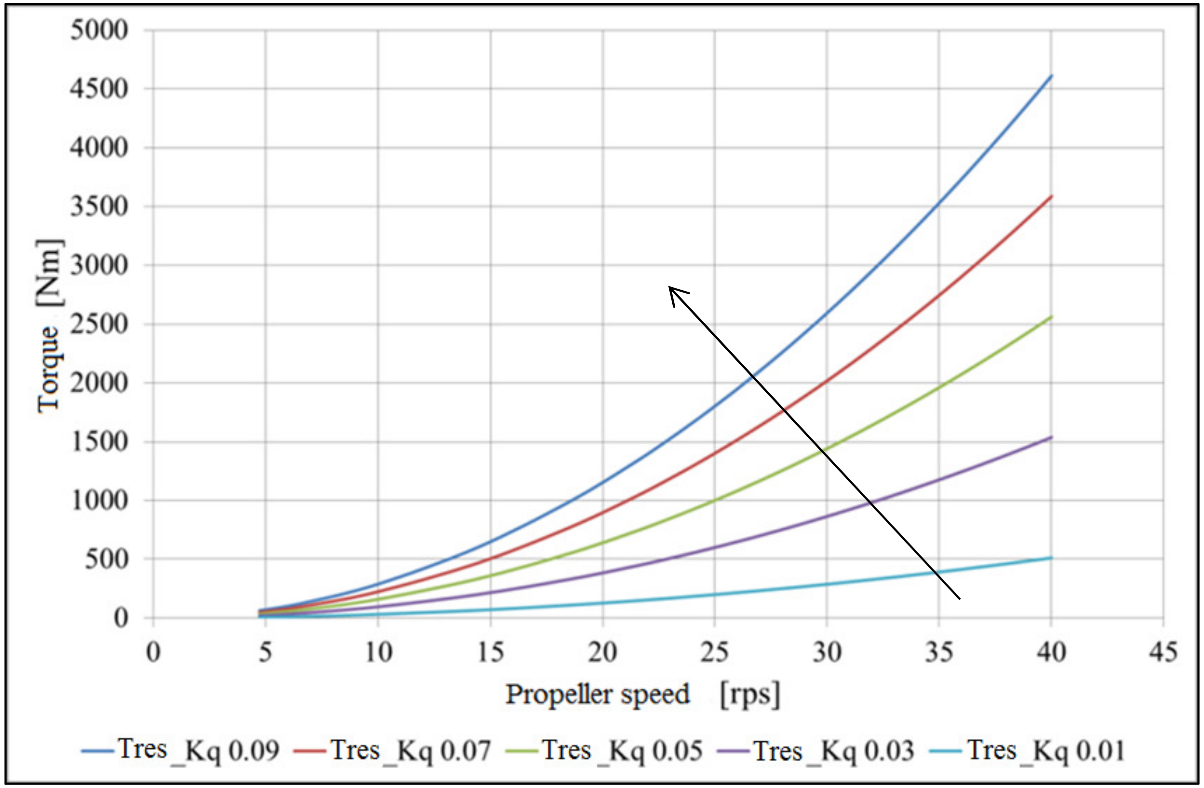
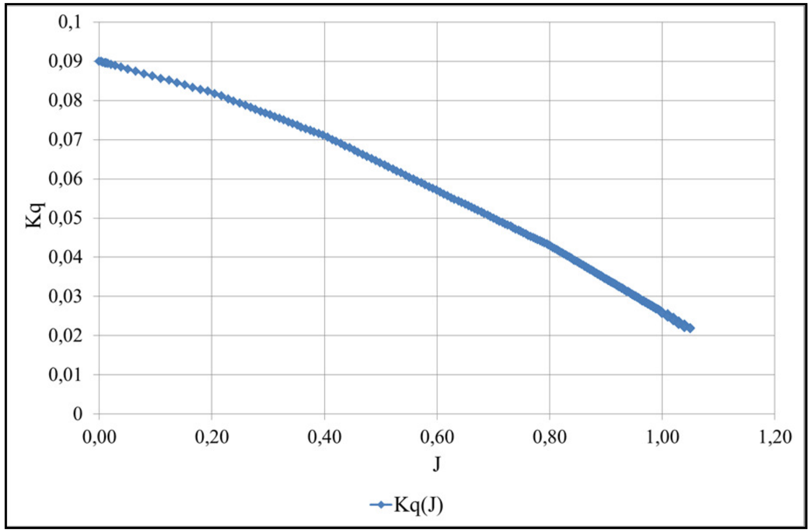
Results

- Brake torque at the propeller shaft → $Q = K_Q \rho n^2 d^5$
  - ✓ Graphic in function of the torque coefficient K_Q(J)
    - Quadratic trend in function of the rotational speed





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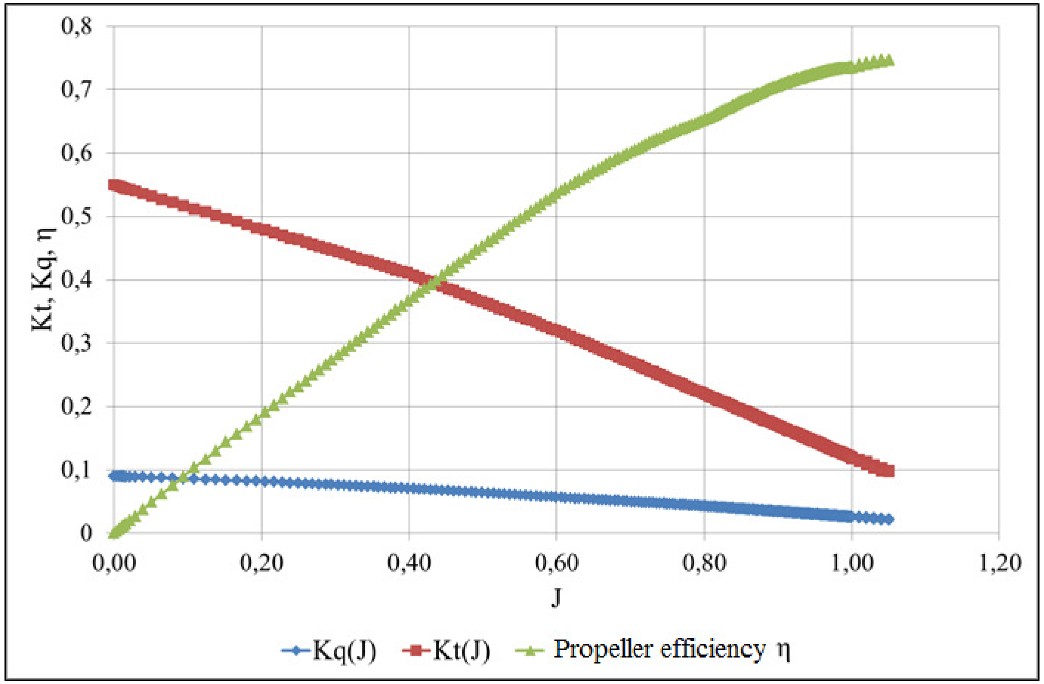
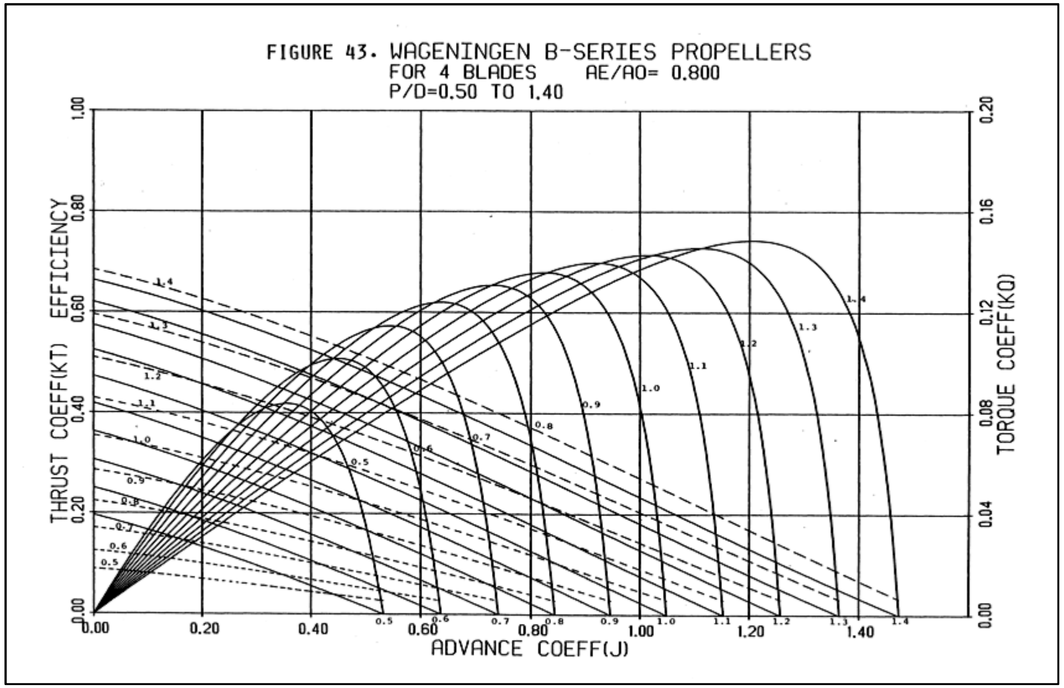
Results

- Trend of the dimensionless coefficients of the propeller

Numerical model



Experimental (from literature)



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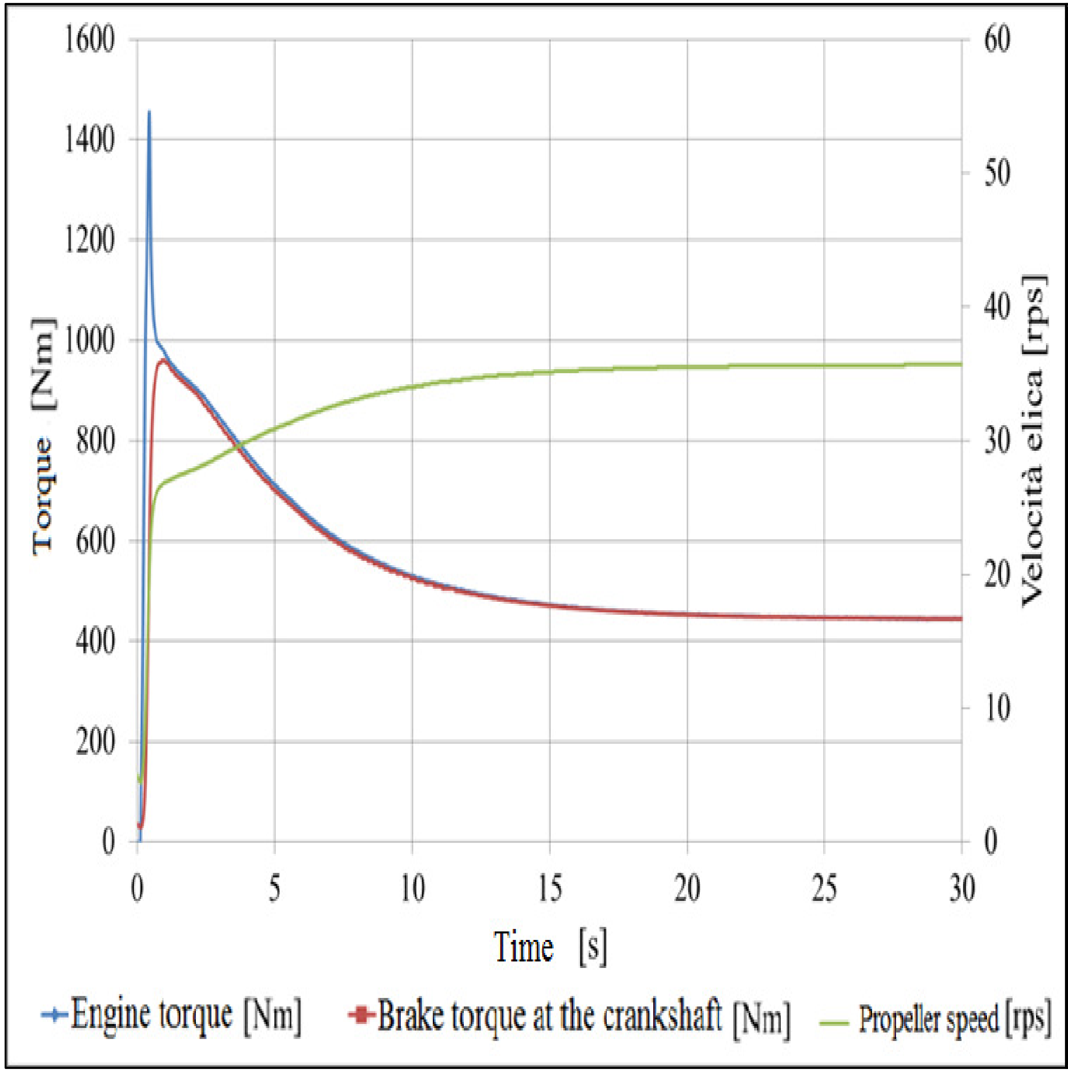
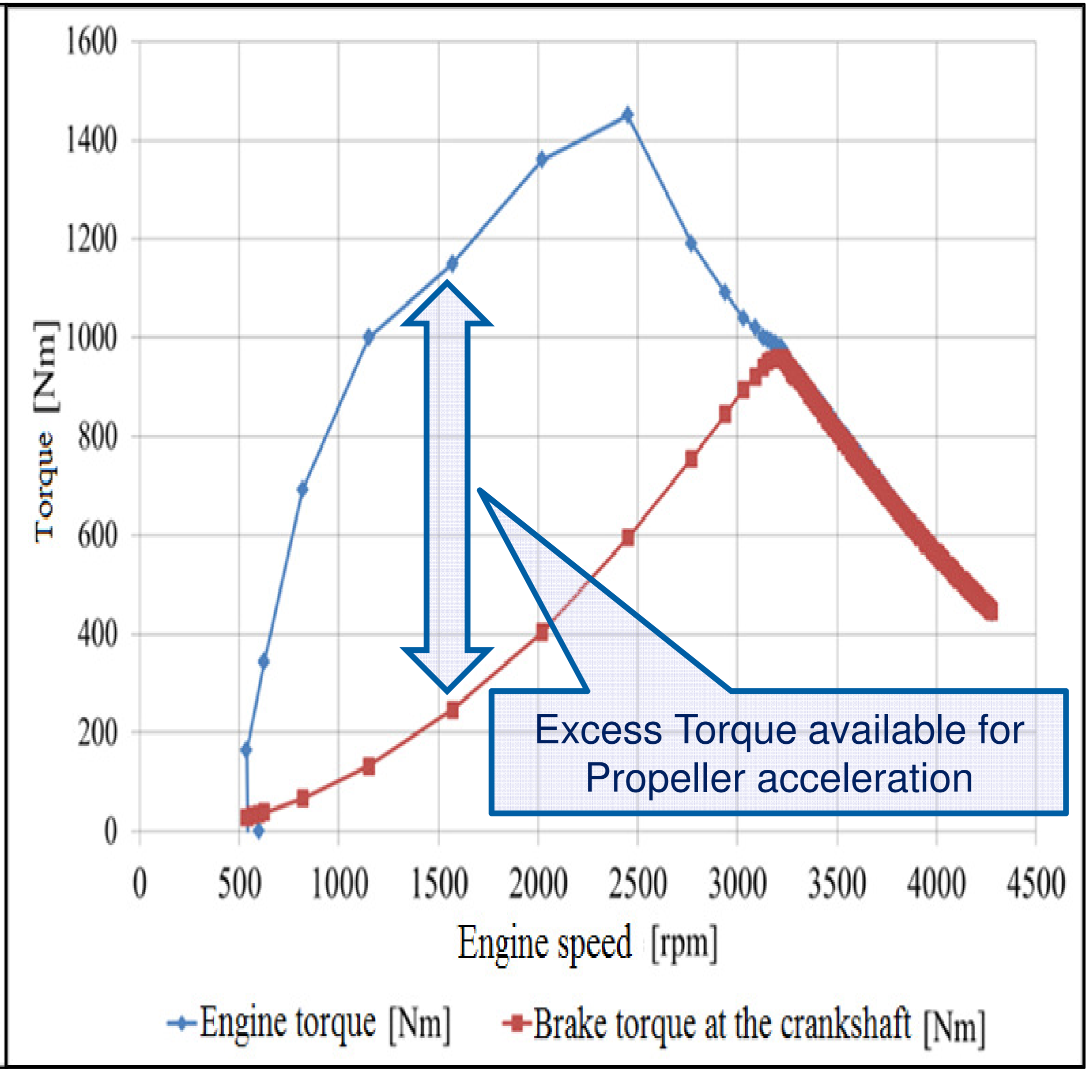
Simulation Results: Transmission dynamics

- Engine torque and Brake torque at the crankshaft in function of time





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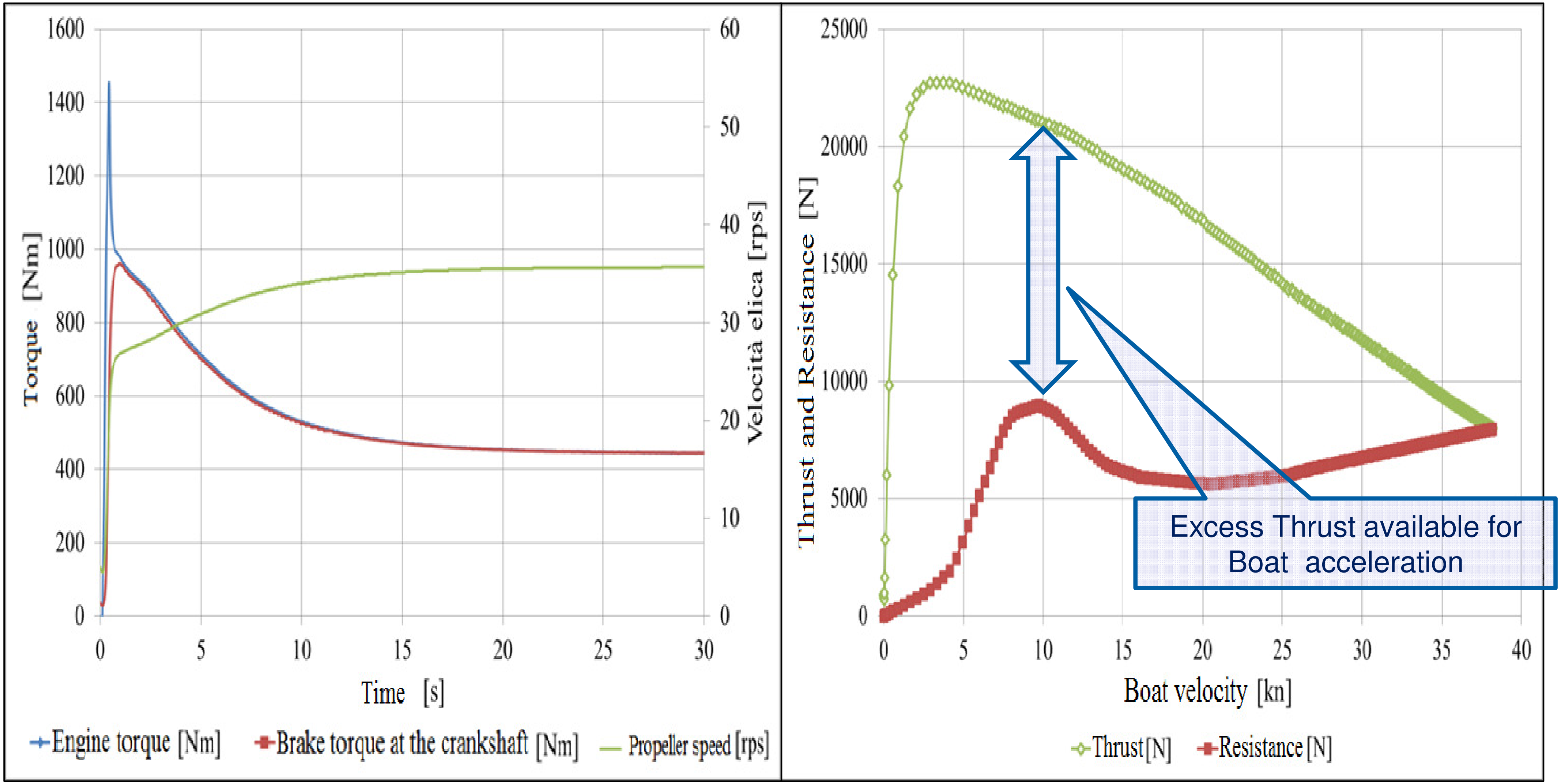
Simulation Results: Transmission dynamics

- Thrust vs Resistance in function of the boat velocity



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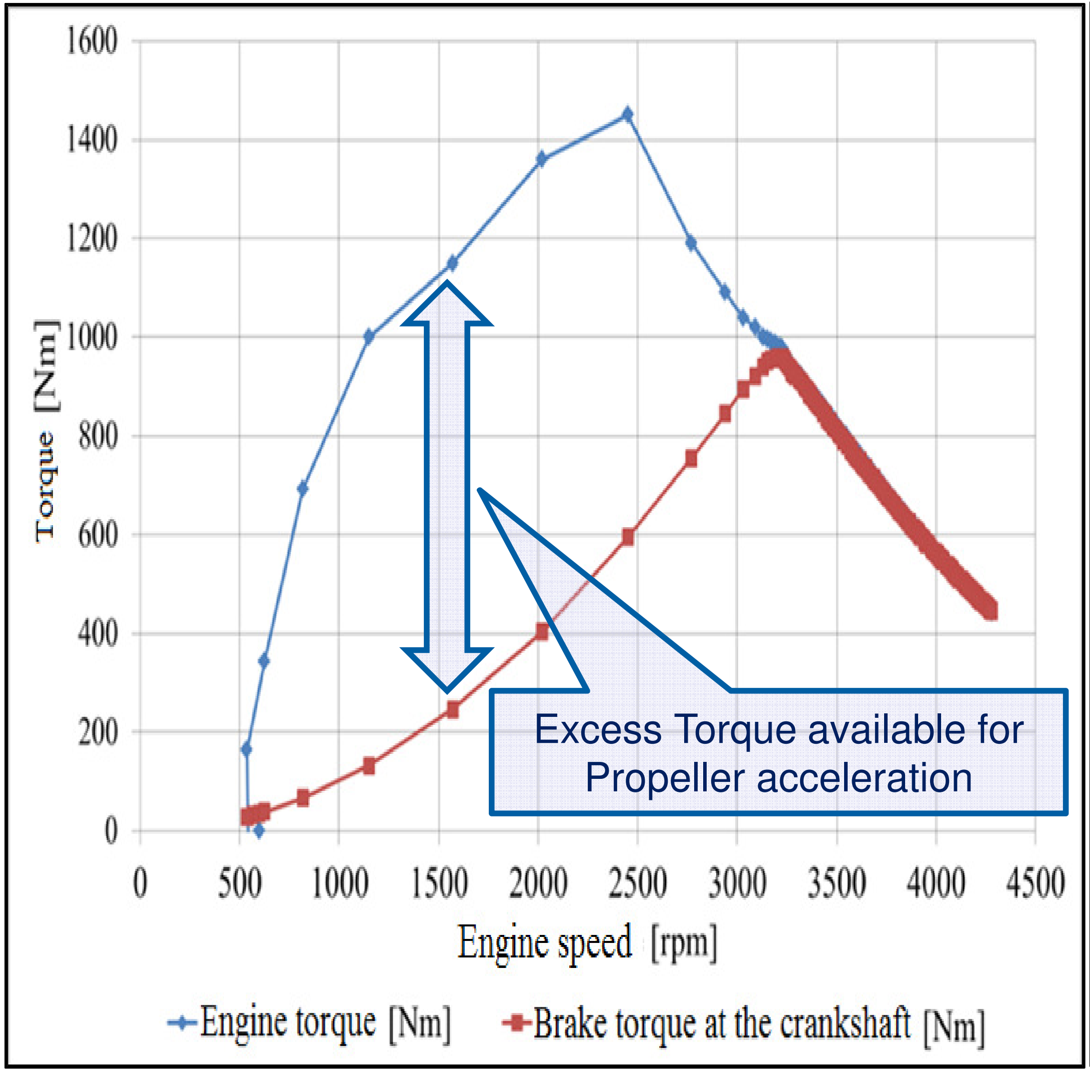
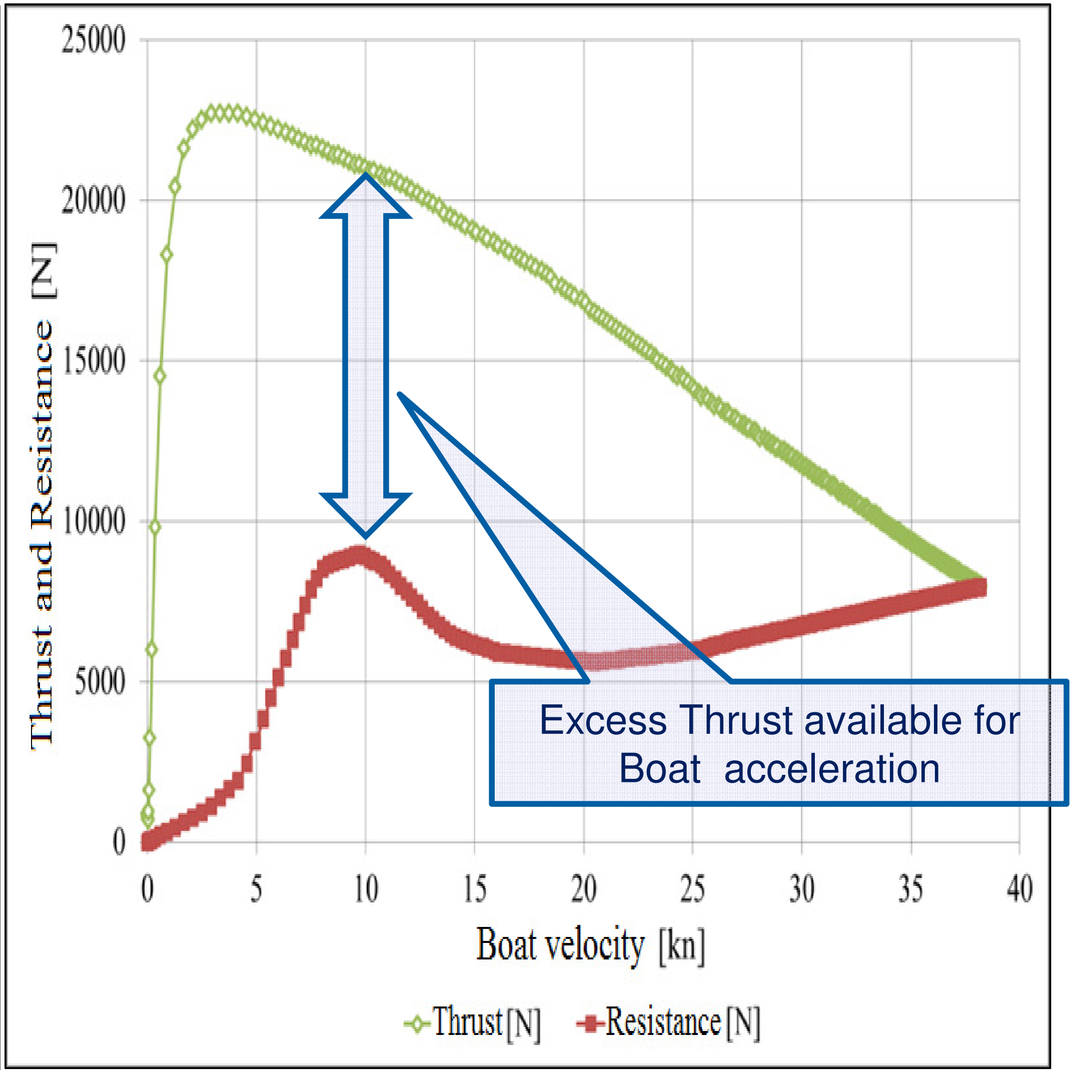
Simulation Results: Transmission dynamics

➢ Propeller Thrust vs Engine Torque for boat acceleration





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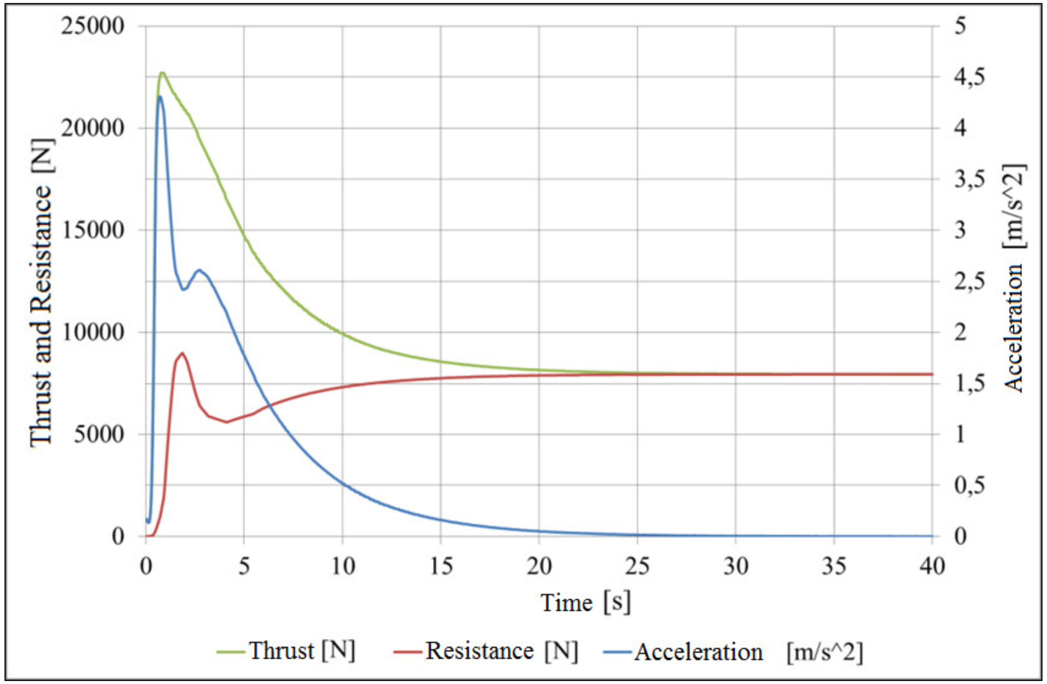
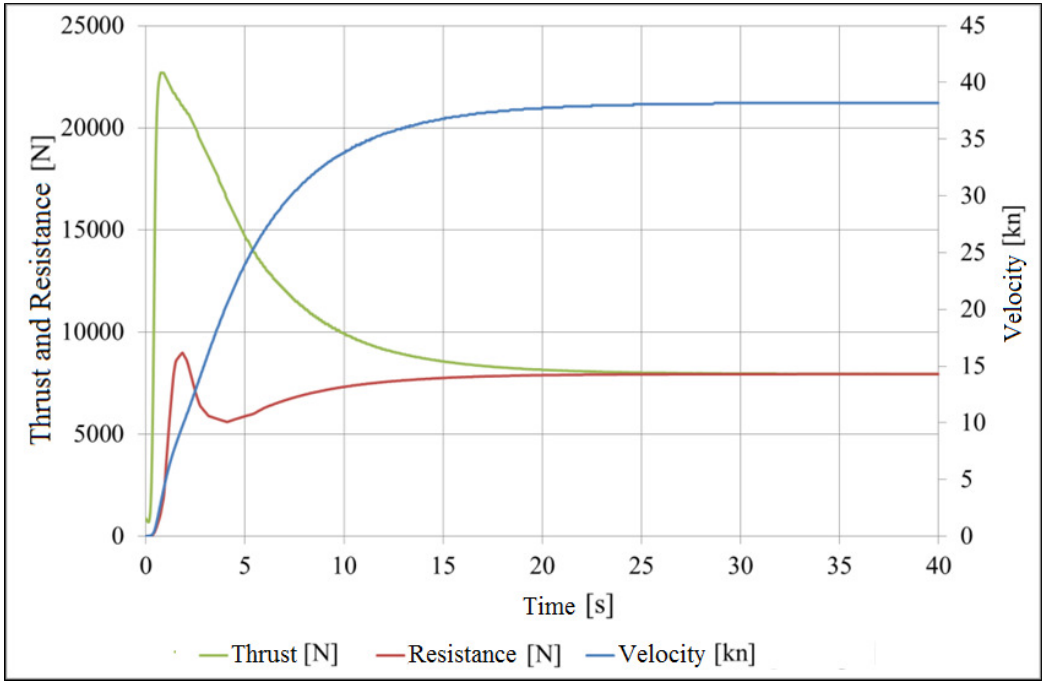
Results

- Thrust – Resistance – Acceleration – Velocity in function of the time

Acceleration



Velocity



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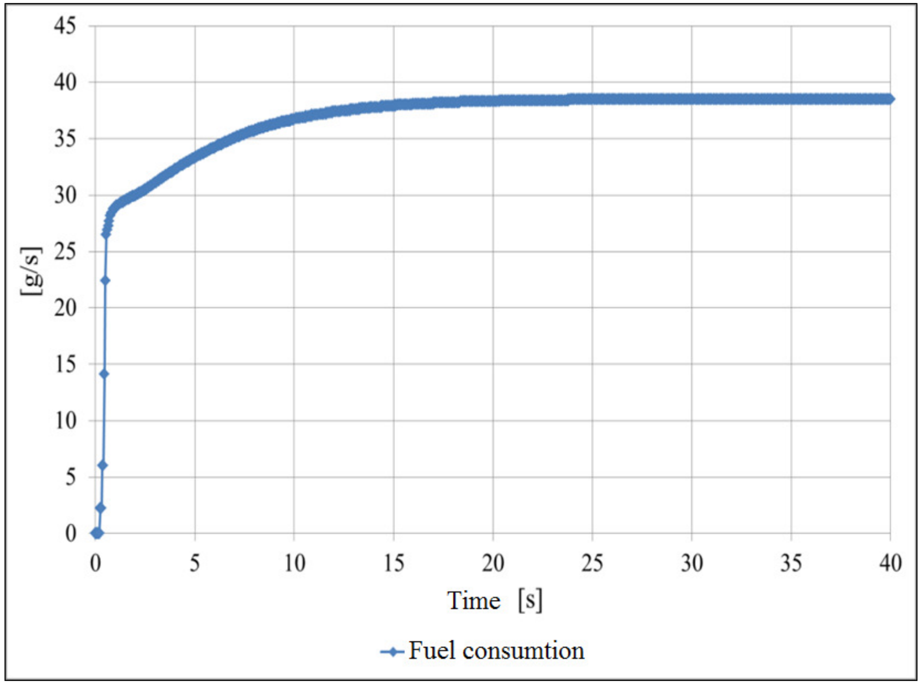
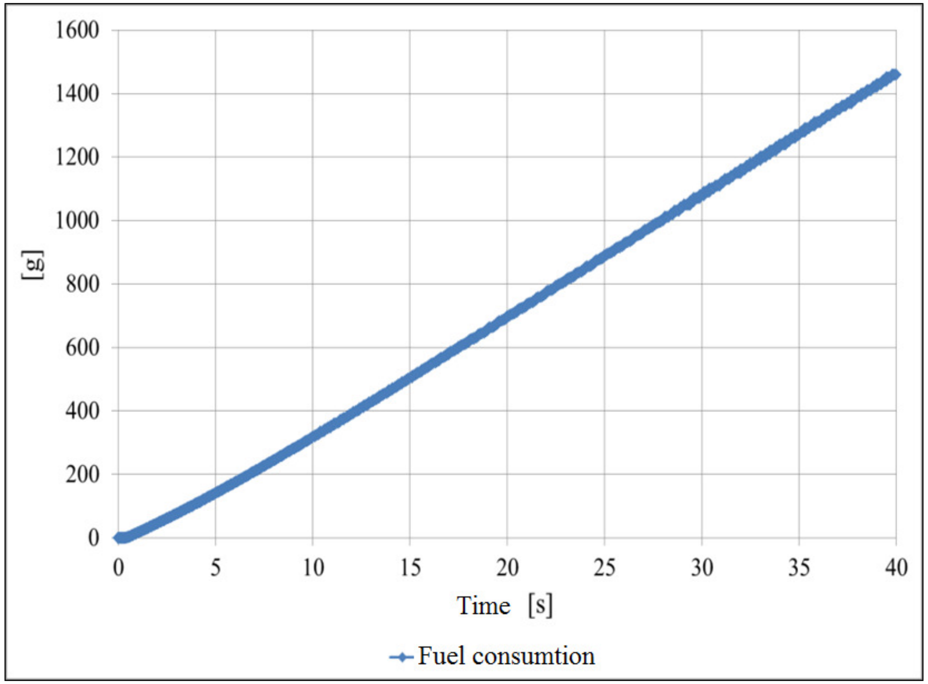
Results

- Brake specific fuel consumption





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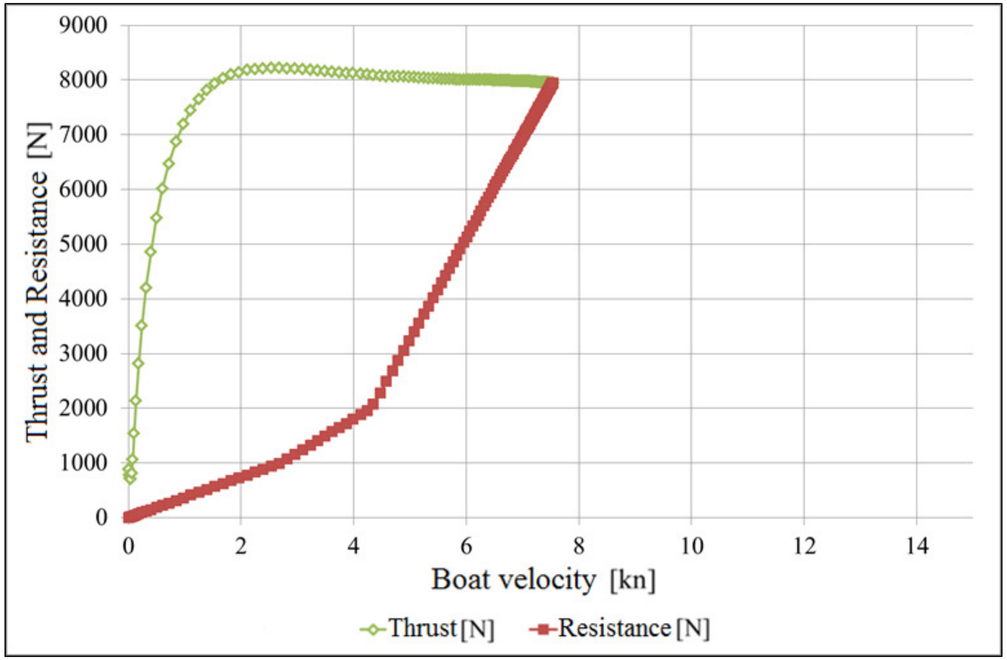
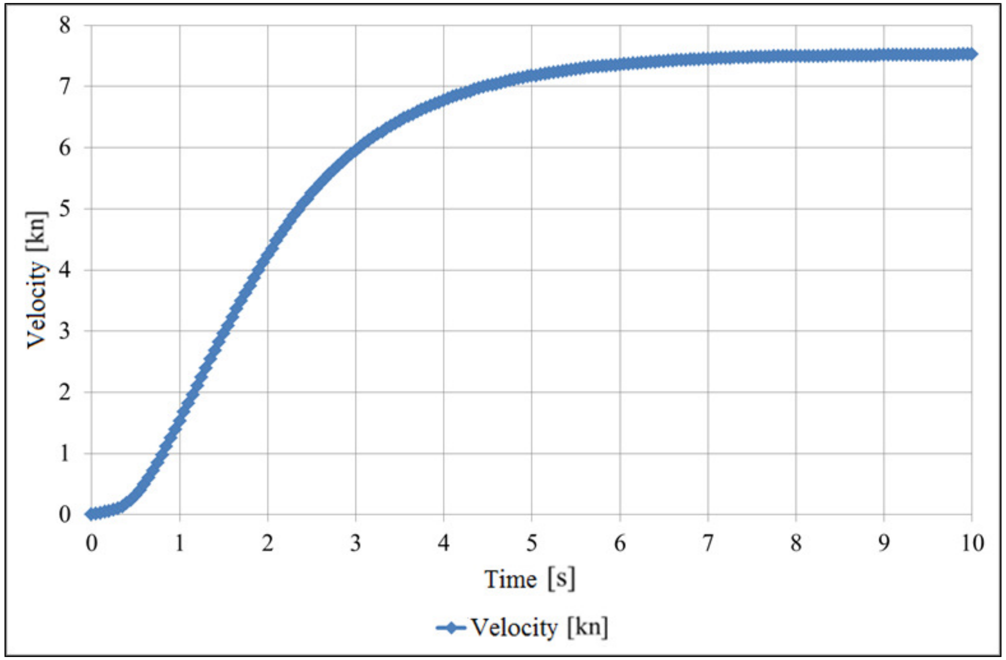
Model Validation in a failure case

- Simulation of the failure to reach the planing phase
  - ✓ Input: reduction of the torque and power of the engine
  - ✓ Result
    - The boat doesn't reach the planing condition
    - Reduction of the maximum boat speed





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Conclusions

- First step of development of an integrated engine-boat model for planing hull
  - ✓ Turbocharger engine → analysis of the coupling between engine and turbo
  - ✓ Engine model integrated with a simplified model of the boat longitudinal dynamic
    - Simulation of the boat acceleration and the transition from displacement to planing phase
    - The model's reliability is verified by comparison with literature data

- Future development
  - ✓ Mathematical implementation of the motion resistance equation
  - ✓ Mathematical implementation for the analysis of surface propellers
  - ✓ Coupling with an electrical turbo in order to promote the transition to the planing phase
    - Turbocharger used to recover the surplus energy
  - ✓ Integration with WAVE RT
  - ✓ Experimental validation of the model

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