# Energy Sensitivity Metric for Route Planning

Objective: Estimate the *sensitivity of the energy consumed by ship propulsion* due to wind, surface waves, current, ship speed, and route deviations.

Assume:

1. Net coefficient of water resistance $\zeta_T$ under pristine METOC conditions (no wind, surface waves, or current)
2. Expected average power-speed ($P$-$V$) characteristics roughly follow Bernoulli's law for motion through incompressible fluid, whereby the *available* power for propulsion required to maintain a given speed is $P \approx \zeta_T V^3$

Result:

$$\Delta E_{rel} = \left[\frac{\zeta_A}{\zeta_T}\frac{V_{HW}}{V}\left(\frac{2V + V_{HW}}{V}\right) + 2\frac{\Delta V}{V} + \frac{c}{V} + \frac{T_{waves}}{\zeta_T V^2} + \frac{\Delta L}{L}\right] \times 100\ \% \tag{1}$$

$\Delta E_{rel}$ Propulsion energy lost to wind, waves, current, speed changes, and course deviations, *relative* to the propulsion energy consumed when sailing the shortest route under pristine weather conditions (all factors zero). Positive $\Delta E_{rel}$ indicates increased energy consumption (loss); negative $\Delta E_{rel}$ indicates decreased consumption (gain).

$\zeta_A$ Coefficient of air resistance against the forward motion of the ship. $\zeta_A \approx \rho_A A/2$; $\rho_A$ being the density of air, and $A$ the effective area of the ship creating air resistance against forward motion.

$\zeta_T$ Coefficient of resistance of the ship under pristine sailing conditions, estimated by hull analysis or from actual $P$-$V$ data.

$V$ Ship forward speed through the water in steady-state conditions.

$V_{HW}$ True head-wind speed; *positive* when *opposing* the ship's forward motion. Equation (1) assumes $V_{HW} + V > 0$ (air opposition), which is typical while underway at medium to full speed.

$\Delta V$ Additional change in speed (throttle) made at the discretion of the crew, perhaps as a fuel-reduction measure, or due to greater certainty in estimated time of arrival through route planning, compensating against ocean current, or as a counter piracy measure.

$c$ *Longitudinal* component of ocean-current speed left *un*compensated by a change $\Delta V$ in speed (throttle). *Positive* current $c$ *opposes* ship forward motion.

$T_{waves}$ Ship resistance due to surface waves, requiring analysis beyond the scope of this note.

$L$ Length of the shortest route subject to voyage constraints.

$\Delta L$ Increase in route length owing to deviations from the shortest route, owing to route planning, to capitalize on (or avoid) foreseen METOC conditions; always a loss inasmuch as $\Delta L \geq 0$.

Averaging The metric (1) can be applied to a pattern of sailing activity by averaging the terms on both sides across a distribution of voyage activity (speeds $V, \Delta V, \Delta L$) and METOC conditions ($V_{HW}, c, T_{waves}$).

Comparing Conditions The energy lost under conditions *B* relative to those lost under conditions *A* can be estimated (to first order) by the difference $\Delta E_{rel}$ for *B* minus $\Delta E_{rel}$ for *A*.

Example: From an analysis of actual sailing data collected from the passenger ship, *MS Rotterdam*, one finds that it is characterized by the ratio $\zeta_A/\zeta_T = 0.014$. Assuming ship speed $V = 20$ knots, $\Delta V = 0$, oppositional head-wind $V_{HW} = 30$ knots, favourable current $c = -0.1$ knots, negligible impact from waves $T_{waves} \approx 0$, and the shortest route $\Delta L = 0$, equation (1) gives $\Delta E_{rel} = 6.9$ % (loss). For comparison, with *no* wind but the same favourable current, $\Delta E_{rel} = -0.5$ % (gain).

Disclaimer: Equation (1) was developed and is under test in NAVTRONIC. It is floated here for discussion purposes. Its derivation and elaboration are in NAVTRONIC deliverables.

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*Prepared by Ronald Kessel, NATO STO CMRE, 08-May-2013, Kessel@cmre.nato.int*
*NATO STO Center for Maritime Research & Experimentation (CMRE),*
*Viale San Bartolomeo 400, La Spezia, 19126 Italy.*