Reduction of Fuel Consumption by Using Automatic Path-Following Systems

A. Lutz, Prof. Dr.-Ing. E.D. Gilles
Institute for System Dynamics, University of Stuttgart, Germany

CCNR Workshop on Inland Navigation CO₂ emissions, 12th April 2011
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1 Introduction

2 Calculation of Fuel Consumption

3 Optimization of Fuel Consumption

4 Summary and Outlook
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1 Introduction

2 Calculation of Fuel Consumption

3 Optimization of Fuel Consumption

4 Summary and Outlook
Hardware:

- Navigation computer
- Sensors to measure the dynamic state
- Sensors to capture information about the environment
- Access to the rudder
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- Navigation computer
- Sensors to measure the dynamic state
- Sensors to capture information about the environment
- Access to the rudder
Software: (based on Radarpilot $720^\circ$)

- ECDIS chart
- Radar object tracking (fusion with AIS)
- Map matching: ECDIS chart with radar image
- Ranges of encounter for collision avoidance
- Guiding lines
Software

Software: (based on Radarpilot 720°)

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- ECDIS chart
- Radar object tracking (fusion with AIS)
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- Ranges of encounter for collision avoidance
- Guiding lines: Track control (1σ accuracy: approx. 2m)
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4 Summary and Outlook
Resistance

Total resistance as in [1], [2], [3]

\[ R_{total} = R_F + R_{App} + R_W + R_{Tr} + R_A + R_{Add} \]

- \( R_F \): frictional resistance
- \( R_{App} \): resistance of appendages
- \( R_W \): wave making and wave breaking resistance
- \( R_{Tr} \): resistance due to stern shape
- \( R_A \): model-ship correlation resistance
- \( R_{Add} \): additional resistance, e.g. wind
Total resistance as in [1], [2], [3]

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Total resistance as in [1], [2], [3]

\[ R_{total} = R_F + R_{App} + R_W + R_{Tr} + R_A + R_{Add} \]

\[ = f(u_{rel}, d, \ldots) \]

- \( R_F \) ... frictional resistance
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\( u_{rel} \) ... Relative velocity
\( d \) ... Depth
Required power, efficiency and fuel consumption

\[ P_{\text{req}} = R_{\text{total}} \, u_{\text{rel}} \]

\[ P_{\text{del}} = \eta_p \, \eta_s \, \eta_g \, P_e \]

\[ P_e = B_e/b_e \quad \text{with} \quad B_e = \dot{V} \, \rho \]

- \( P_{\text{req}} \) ... Required power
- \( P_{\text{del}} \) ... Delivered power
- \( P_e \) ... Engine power
- \( u_{\text{rel}} \) ... Relative velocity
- \( \eta_p \) ... Propulsion efficiency
- \( \eta_s \) ... Shaft efficiency
- \( \eta_g \) ... Gear efficiency
- \( B_e \) ... Fuel flow rate
- \( b_e \) ... Specific fuel consumption
- \( \dot{V} \) ... Fuel volume
- \( \rho \) ... Fuel density

\[
\int_{t_0}^{t_f} R_{\text{total}} \, u_{\text{rel}} \, dt
\]

Fuel consumption
Required power, efficiency and fuel consumption

\[ P_{\text{req}} = R_{\text{total}} \ u_{\text{rel}} \]
\[ P_{\text{del}} = \eta_p \ \eta_s \ \eta_g \ P_e \]
\[ P_e = B_e / b_e \quad \text{with} \quad B_e = \dot{V} \ \rho \]

- **Required power**
- **Delivered power**
- **Engine power**

\[ u_{\text{rel}} \ldots \text{Relative velocity} \]
\[ \eta_p \ldots \text{Propulsion efficiency} \]
\[ \eta_s \ldots \text{Shaft efficiency} \]
\[ \eta_g \ldots \text{Gear efficiency} \]

- **\( B_e \) . . . Fuel flow rate**
- **\( b_e \) . . . Specific fuel consumption**
- **\( V \) . . . Fuel volume**
- **\( \rho \) . . . Fuel density**
### Required power, efficiency and fuel consumption

\[ P_{\text{req}} = R_{\text{total}} u_{\text{rel}} \]

\[ P_{\text{del}} = \eta_p \eta_s \eta_g P_e \]

\[ P_e = B_e/b_e \quad \text{with} \quad B_e = \dot{V} \rho \]

- **Required power**
- **Delivered power**
- **Engine power**

- \( u_{\text{rel}} \) ... Relative velocity
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- \( B_e \) ... Fuel flow rate
- \( b_e \) ... Specific fuel consumption
- \( V \) ... Fuel volume
- \( \rho \) ... Fuel density

\[ \int_{t_0}^{t} B_e \rho R_{\text{total}} u_{\text{rel}} \eta_p \eta_s \eta_g \, dt \]

Fuel consumption
Engine and Propulsion System

Required power, efficiency and fuel consumption

\[ P_{\text{req}} = R_{\text{total}} \ u_{\text{rel}} \]
\[ P_{\text{del}} = \eta_p \ \eta_s \ \eta_g \ P_e \]
\[ P_e = B_e / b_e \quad \text{with} \quad B_e = \dot{V} \ \rho \]

- Required power
- Delivered power
- Engine power

\( u_{\text{rel}} \ldots \) Relative velocity
\( \eta_p \ldots \) Propulsion efficiency
\( \eta_s \ldots \) Shaft efficiency
\( \eta_g \ldots \) Gear efficiency

\( B_e \ldots \) Fuel flow rate
\( b_e \ldots \) Specific fuel consumption
\( V \ldots \) Fuel volume
\( \rho \ldots \) Fuel density
## Required power, efficiency and fuel consumption

\[
P_{\text{req}} = R_{\text{total}} \cdot u_{\text{rel}}
\]

\[
P_{\text{del}} = \eta_p \cdot \eta_s \cdot \eta_g \cdot P_e
\]

\[
P_e = \frac{B_e}{b_e} \quad \text{with} \quad B_e = \dot{V} \rho
\]

- **Required power**
- **Delivered power**
- **Engine power**

\(u_{\text{rel}}\) ... Relative velocity
\(\eta_p\) ... Propulsion efficiency
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\(B_e\) ... Fuel flow rate
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\(\dot{V}\) ... Fuel volume
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Engine and Propulsion System

Required power, efficiency and fuel consumption

\[ P_{req} = R_{total} \ u_{rel} \]

\[ P_{del} = \eta_p \ \eta_s \ \eta_g \ P_e \]

\[ P_e = B_e / b_e \quad \text{with} \quad B_e = \dot{V} \ \rho \]

\[ u_{rel} \ldots \text{Relative velocity} \]
\[ \eta_p \ldots \text{Propulsion efficiency} \]
\[ \eta_s \ldots \text{Shaft efficiency} \]
\[ \eta_g \ldots \text{Gear efficiency} \]

\[ \downarrow P_{req} = P_{del} \]

\[ V = \int_{0}^{t} \frac{b_e}{\rho} \frac{R_{total} \ u_{rel}}{\eta_p \ \eta_s \ \eta_g} \ dt \]

\[ B_e \ldots \text{Fuel flow rate} \]
\[ b_e \ldots \text{Specific fuel consumption} \]
\[ V \ldots \text{Fuel volume} \]
\[ \rho \ldots \text{Fuel density} \]

Fuel consumption
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Rhine River, km 520-540
Rhine River, km 520-540

Depth from BAW

Current from BAW
Rhine River, km 520-540

<table>
<thead>
<tr>
<th>Section</th>
<th>Location [km]</th>
<th>Current [m/s]</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>520-525</td>
<td>1.0</td>
<td>4.1</td>
</tr>
<tr>
<td>2</td>
<td>525-530</td>
<td>0.8</td>
<td>4.4</td>
</tr>
<tr>
<td>3</td>
<td>530-532.5</td>
<td>2.1</td>
<td>4.7</td>
</tr>
<tr>
<td>4</td>
<td>532.5-539</td>
<td>1.7</td>
<td>4.9</td>
</tr>
<tr>
<td>5</td>
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Rhine River, km 520-540

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→ Optimization problem: How fast in which section in order to reach destination in time while minimizing fuel?
Velocity Optimization

Simulation specifications

- Ship length: 105 m, width: 9.5 m, draft: 2.7 m
- Engine power: 1000 kW, spec. fuel consumption: 0.18 kg/kWh
- Upstream, Traveling time 3h ($u_{\text{abs}} \approx 7$ km/h)
Velocity Optimization

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- Ship length: 105 m, width: 9.5 m, draft: 2.7 m
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<tbody>
<tr>
<td>1</td>
<td>520-525</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>525-530</td>
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<td>10</td>
</tr>
<tr>
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\[
u_{\text{opt}} \quad B_{\text{opt}} = 0.169 m^3 \\
u_{\text{abs}} = c \quad B_{\text{abs}} = 0.170 m^3 \\
u_{\text{rel}} = c \quad B_{\text{rel}} = 0.174 m^3
\]
Velocity Optimization

Simulation specifications

- Ship length: 105 m, width: 9.5 m, draft: 2.7 m
- Engine power: 1000 kW, spec. fuel consumption: 0.18 kg/kWh
- Upstream, Traveling time 3h \(u_{\text{abs}} \approx 7\text{km/h}\)

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</tr>
<tr>
<td>Current [m/s]</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
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\[u_{\text{rel}} = u_{\text{abs}} = c, \quad B_{\text{rel}} = 0.2878 \text{m}^3\]

\[u_{\text{opt}}, \quad B_{\text{opt}} = 0.2868 \text{m}^3\]
Velocity Optimization

Simulation specifications

- Ship length: 105 m, width: 9.5 m, draft: 2.7 m
- Engine power: 1000 kW, spec. fuel consumption: 0.18 kg/kWh
- Upstream, Traveling time 3h \( u_{\text{abs}} \approx 7 \text{km/h} \)

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Fuel consumption reduction: 4.0%
## Velocity Optimization

### Simulation specifications

- **Ship length:** 105 m, width: 9.5 m, draft: 2.7 m
- **Engine power:** 1000 kW, spec. fuel consumption: 0.18 kg/kWh
- **Upstream, Traveling time** 4h ($u_{abs} \approx 5\text{km/h}$)

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<tr>
<th>Location [km]</th>
<th>$u_{rel}$ [m/s]</th>
<th>$u_{opt}$</th>
<th>$B_{opt}$ = 0.204 m$^3$</th>
<th>$u_{rel}$ = $c$</th>
<th>$B_{rel}$ = 0.217 m$^3$</th>
<th>$u_{abs}$ = $c$</th>
<th>$B_{abs}$ = 0.209 m$^3$</th>
</tr>
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<tbody>
<tr>
<td>520-525</td>
<td>2.2</td>
<td>3.6</td>
<td></td>
<td>2.8</td>
<td></td>
<td>2.6</td>
<td></td>
</tr>
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**Fuel consumption reduction:** 6.0%
Optimization of Lateral Position

Optimization problem: Where to navigate in lateral direction in order to realize and even increase the expected fuel consumption reduction?
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→ Fuel consumption reduction can only be fully realized with automatic path-following systems on optimal guiding lines.
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Summary

- Resistance calculations from literature
- Fuel consumption reduction by adapting the velocity according to depth and current
- Increase of fuel reduction by precisely navigating along an optimal guiding line
- No vessel modifications necessary

Outlook

- Combined optimization along and across the river → optimal guiding lines
- Investigation at different water levels for different vessels
- Experimental validation
Proposal for validation on the Rhine, **ARGO 2**

- 20 vessels with navigation system, automatic path-following system and fuel consumption measurement equipment
- River data from Bundesanstalt für Wasserbau (BAW)
- Optimal guiding lines for each vessel and water level
- Comparison between optimal and manual navigation
- Expected fuel consumption reduction: Up to 10%
- Expected cost: ≈ 2.0 Mio. €
- Amortization: ≈ 8 months
Thank you for your attention

Reduction of Fuel Consumption by Using Automatic Path-Following Systems

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