Advanced Thin-Haul Concept Studies
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Joby Aviation

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# Comparison of specifications

<table>
<thead>
<tr>
<th></th>
<th>Cessna 402C</th>
<th>Tecnam P2012</th>
<th>Pilatus PC-12</th>
<th>Advanced concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>875 nm</td>
<td>620 nm</td>
<td>1,845 nm</td>
<td>400 nm</td>
</tr>
<tr>
<td>Stall speed (CAS)</td>
<td>67 kt</td>
<td>60 kt</td>
<td>67 kt</td>
<td>67 kt</td>
</tr>
<tr>
<td>Takeoff run</td>
<td>1,763 ft</td>
<td>1,410 ft</td>
<td>1,480 ft</td>
<td>2,000 ft</td>
</tr>
<tr>
<td>Seats</td>
<td>10</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Engine(s)</td>
<td>TSIO-520</td>
<td>TEO-540</td>
<td>PT6A</td>
<td>Varies</td>
</tr>
<tr>
<td>Total power</td>
<td>650 hp</td>
<td>700 hp</td>
<td>1,200 hp</td>
<td>Varies</td>
</tr>
<tr>
<td>Retractable gear</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Max cruise speed</td>
<td>194 KTAS</td>
<td>210 KTAS</td>
<td>285 KTAS</td>
<td>180-325 KTAS</td>
</tr>
<tr>
<td>Pressurized</td>
<td></td>
<td></td>
<td>✓</td>
<td>Varies</td>
</tr>
</tbody>
</table>
Cessna 402

Tecnam P2012

Pilatus PC-12
Advanced design configurations

Turbodiesels or turboprops

Electric motors with turbodiesel or turbine range extender
Mission descriptions

Electric

- 100 nm economy cruise (≥180kt, 8,000-10,000 ft)

Hybrid

- 67 nm alternate

Hybrid

- 45 min IFR reserve

Hybrid

- 400 nm high-speed cruise (180-325 kt, 8,000-25,000 ft)

Hybrid

- 67 nm alternate

Hybrid

- 45 min IFR reserve
Lowest battery+electricity cost  Lowest gross weight  Lowest total cost
Operating costs for 180 kt, 100 nm flight

<table>
<thead>
<tr>
<th></th>
<th>Cost per nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>C402</td>
<td>$3.50</td>
</tr>
<tr>
<td>P2012</td>
<td>$3.20</td>
</tr>
<tr>
<td>PC-12</td>
<td>$6.00</td>
</tr>
<tr>
<td>C</td>
<td>$4.20</td>
</tr>
<tr>
<td>3M</td>
<td>$3.00</td>
</tr>
<tr>
<td>HLP</td>
<td>$3.10</td>
</tr>
</tbody>
</table>
100 nm flight costs

Cruise speed for 400 nm flight (KTAS)
Total combustion engine power (kW) vs. Cruise speed for 400 nm flight (KTAS)

- C (diesel)
- 3M (diesel)
- HLP (diesel)
- C (turbine)
- 3M (turbine)
- HLP (turbine)
- P2012
- C402
- PC-12
Acknowledgements

• NASA Langley (Dr. Nick Borer, Bill Fredericks, Ken Goodrich, Mark Moore, Michael Patterson)

• Dr. Joachim Grenestedt
Future Work

• CFD validation of current designs
• Boundary layer ingestion propeller analysis
• Aeroelastic analysis
• Additional configuration analysis (e.g. twin boom)
400 nm flight costs

**Graph 1:**
- **Total cost/nm**
- **Cruise speed for 400 nm mission (KTAS)**
- **Models:**
  - C (diesel)
  - 3M (diesel)
  - HLP (diesel)
  - C (turbine)
  - 3M (turbine)
  - HLP (turbine)
  - P2012
  - C402
  - PC-12

**Graph 2:**
- **Battery + electricity + fuel cost/nm**
- **Cruise speed for 400 nm mission (KTAS)**
- **Models:**
  - C (diesel)
  - 3M (diesel)
  - HLP (diesel)
  - C (turbine)
  - 3M (turbine)
  - HLP (turbine)
  - P2012
  - C402
  - PC-12
Energy cost sensitivity for 400 nm flight

Cruise speed for 400 nm flight (KTAS) vs. Total cost/nm for 400 nm flight

Symbols and colors represent different variables and models:
- C $3.50/gal
- C $5.50/gal
- W 7¢/kWh
- WL 7¢/kWh
- P2012 $3.50/gal
- P2012 $5.50/gal
- C402 $3.50/gal
- C402 $5.50/gal
- PC-12 $3.50/gal
- PC-12 $5.50/gal

Costs and energy prices vary between different models and fuel types.

The graph shows the total cost per nm for various cruise speeds, with cost sensitivity for energy inputs ranging from $0.00 to $7.00 per nm.
Specific energy sensitivity

Total cost/nm for 100 nm mission

Cruise speed for 400 nm flight (KTAS)
Effect of high-lift propellers

Cruise speed for 400 nm flight (KTAS)

Wing loading (lb/ft²)

C/3M  HLP (diesel)  HLP (turbine)
P2012  C402  PC-12
## Engine options for advanced concepts

<table>
<thead>
<tr>
<th></th>
<th>Turbodiesel</th>
<th>Turboprop</th>
<th>Turbine generator (recuperated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFC (lb/hp/hr)</td>
<td>0.36-0.41</td>
<td>0.63</td>
<td>0.45</td>
</tr>
<tr>
<td>TBO</td>
<td>2,400 hours</td>
<td>3,600 hours</td>
<td>6,000 hours</td>
</tr>
<tr>
<td>Critical altitude</td>
<td>10,000 ft</td>
<td>Sea level</td>
<td>Sea level</td>
</tr>
<tr>
<td>Specific power</td>
<td>0.48 hp/lb</td>
<td>2.1 hp/lb</td>
<td>2.0 hp/lb</td>
</tr>
<tr>
<td>Cost per 100 hp</td>
<td>$39,000</td>
<td>$56,000</td>
<td>$56,000</td>
</tr>
<tr>
<td>Minimum size</td>
<td>230 shp</td>
<td>250 shp</td>
<td>250 shp</td>
</tr>
</tbody>
</table>
Operating cost components

- Battery amortization (2,000 cycles, 20¢/kWh)
- Electricity (industrial rate: 7¢/kW)
- Fuel ($3.50/gal)
- Overhaul reserve
- Depreciation (30,000 hours)
- Interest
- Pilot
- Maintenance
- Insurance
- Landing fees
Operating costs for the 180 kt, 100 nm mission

Cost per nm for 100 nm flight

- Battery
- Electricity
- Overhaul
- Fuel
- Depreciation
- Interest
- Pilot
- Maintenance
- Insurance
- Landing fees

- C402
- P2012
- PC-12
- C
- 3M
- HLP
Aircraft unit cost model

HLP cost (325 kt turbine)

[Graph showing cost against production quantity for HLP (325 kt turbine), HLP (180 kt diesel), and P2012, with detailed breakdowns for various cost factors such as profit, engine+motors, avionics, materials, QC, Mfg labor, tooling, Flt test, Dev support, and Engineering.]
Weighted total cost (75% 100nm, 25% 400nm) vs. Cruise speed for 400 nm flight (KTAS).

- **C (diesel)**
- **3M (diesel)**
- **HLP (diesel)**
- **C (turbine)**
- **3M (turbine)**
- **HLP (turbine)**
- **P2012**
- **C402**
- **PC-12**